Value Creation through Co-Opetition in Service Networks

Zur Erlangung des akademischen Grades eines
Doktors der Wirtschaftswissenschaften

(Dr. rer. pol.)

von der Fakultät für
Wirtschaftswissenschaften
des Karlsruher Instituts für Technologie (KIT)

genehmigte
Dissertation

von

Dipl.-Inform.Wirt Tobias Daniel Conte

Tag der mündlichen Prüfung: 25.06.2010
Referent: Prof. Dr. Christof Weinhardt
Korreferent: Prof. Dr. Gerhard Satzger

Karlsruhe, 2010

Abstract

Once serving the whole value chain by what has become known as vertical integration, companies have long since started to outsource value creation processes to specialized partners. Moreover, societal changes have induced a paradigm shift from product-driven to service-dominated value creation. Capabilities of information technology lets both of these developments take a new dimension. Well-defined interfaces and standardization as fundamental concepts of service orientation bring about a high degree of interoperability, which enables companies to establish multiple linkages and to combine capabilities and assets from diverse parties. Significant business impact of such tendencies can be observed in the software industry. Already shaken by the fundamental transition from selling traditional software products to the provisioning of on-demand services, a second wave of innovation includes the specialization and modularization of services, giving way to complex services composed of modules offered by diversified providers. Coordination of participants takes place in highly agile and modular service value networks (SVNs) that exploit the power of combinatorics credited to Web services: they allow for a flexible recombination of service modules to meet heterogeneous customer demands.

These newly arising networks include both cooperation and competition as inherent building blocks. On the one hand, a certain set of service providers must cooperate in order to create value. On the other hand, substitutive services compete to be included in complex offerings. What is more, partners turn into rivals when it comes to distributing a jointly created surplus which cannot be precisely accredited to the contributors. While the technological side to enabling SVNs already enjoys intensified research activity, economic considerations that include both the co-opetitive environment and the characteristics of (complex) services are lagging behind.

This thesis tackles the challenge of coordinating self-interested, yet partly interdependent service providers by designing an adequate mechanism which shall be capable of handling the duality of cooperation and competition. Taking the viewpoint of a mechanism or network operator of a newly launched SVN, participants' interests need to be aligned with the network's global objectives in an incentive engineering approach. Classic mechanism design focusses on economic properties such as allocative efficiency and incentive compatibility, however, it lacks in objectives that arise from the perspective of network design. Such network-related goals are, among others, healthy network growth, a fair distribution of jointly generated value, or interoperability. Additionally, specific requirements of (Web) services need to be considered. On the one hand, support for the negotiation over diverse non-price attributes that constitute a service's configuration, that is, quality of service (QoS), is of crucial importance. On the other hand, the sequence of service modules determine a complex service's functionality and must, therefore, be captured by the mechanism proposed in this thesis.

Academic literature currently does not yield contributions that cover abovementioned aspects in an integrated effort. In this vein, the work at hand presents a novel mechanism design approach – the co-opetition mechanism – that is tailored to additional requirements imposed both by co-opetitive environments and to crucial characteristics of complex Web services. The latter is addressed by a comprehensive analysis, definition, and formalization of SVNs, which forms the basis for an appropriate bidding language that supports various types of QoS. Co-opetition is captured in the fashion how payments are distributed by the mechanism: the co-opetition mechanism reflects the radically novel concept to not only compensate those providers which are actually allocated for service provisioning, but also to pay out potential value creators "on standby" that are not part of the complex service delivered at a time. In order to capture the potential value created in the system, the power ratio is introduced as a suitable measure. Classic mechanism design properties are not first priority, yet remain in the focus. In order to substantiate this thesis' contribution, desired mechanism properties are evaluated both analytically and numerically.

Rewarding the very contribution of service providers to network formation, the co-opetition mechanism is a promising approach to boost the combinatorial potential of SVNs in their launch phase.

Acknowledgements

This work would not have been possible without the support of several people who contributed with ideas, conversations, guidance, and care. I am especially indebted to my supervisor Prof. Dr. Christof Weinhardt who made available his support in a number of ways. He gave me the very opportunity to pursue my dissertation and continuously provided ideas and advice, at the same time granting the necessary individual freedom. I would also like to thank my co-advisor Prof. Dr. Gerhard Satzger for fruitful discussions that advanced my work on the thesis considerably. Prof. Dr. Martin Ruckes and Prof. Dr. Svetlozar Rachev have been so kind to serve on the board of examiners.

Further, I would like to show my gratitude to the team of the research group on Information and Market Engineering at the Institute of Information Systems and Management (IISM) as well as to the team of the research division on Information Process Engineering (IPE) at the FZI Research Center for Information Technology. I would like to especially thank my advisors Dr. Benjamin Blau, Dr. Clemens van Dinther, and Dr. Carsten Holtmann for their guidance, ideas, and constructive criticism, constantly pushing me and my research into the right direction. Further, I would like to thank Prof. Dr. Dirk Neumann and Jun.-Prof. Dr. Stefan Seifert for their seminal ideas and hints in both the early stage of this research and periods of transition. It is a pleasure to thank Jochen Martin, Rico Knapper, Wibke Michalk, and Yongchun Xu who provided valuable input to my research, both from a technical and a mathematical direction. I would also like to thank my "fellow sufferer" and constant bureau roommate Stephan Stathel not only for lively discussions, but also for providing a relaxed and fun environment.

I dedicate this thesis to my parents Angelika and Carl who have always stood behind me throughout my studies. Finally, I want to thank Juliane for her love and her patience.

Tobias Conte

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AHP	Analytic Hierarchical Processing
API	Application Programming Interface
CRM	Customer Relationship Management
CSA	Complex Service Auction
DFS	Depth First Search
ETF-1	Equal Transfer Function for Allocated Services
ETF-2	Equal Transfer Function for All Participating Services
FMC	Fundamental Modeling Concepts
GDP	Gross Domestic Product
HTTP	Hypertext Transfer Protocol
ICT	Information and Communication Technology
IHIP	Inseparability, Heterogeneity, Intangibility, Perishability
IS	Information Systems
ISE	Integrated Service Engineering
IT	Information Technology
ITF	Interoperability Transfer Function
JSON	JavaScript Object Notation
MACE	Multi-Attribute Combinatorial Exchange
MAUT	Multi-Attribute Utility Theory
NMD	Networked Mechanism Design
OWL	Web Ontology Language
PaaS	Platform-as-a-Service
PBFN	Player-Based Flexible Network
PR	Power Ratio
PRTF	Power Ratio-Based Transfer Function
QoS	Quality of Service
REST	Representational State Transfer
RFQ	Request For Quote
RSS	Really Simple Syndication
SaaS	Software-as-a-Service
SBN	Smart Business Network
SLA	Service Level Agreement
SME	Small and Medium Enterprises
SMP	Service Management Platform
SOAP	Simple Object Access Protocol
SVN	Service Value Network

TSR	Tradable Services Runtime
URI	Uniform Resource Identifier
VCG	Vickrey-Clarke-Groves
W3C	World Wide Web Consortium
WS-BPEL	Web Services Business Process Execution Language
WSDL	Web Services Description Language
XML	eXtensible Markup Language

Part I

Foundations & Preliminaries

Chapter 1

Introduction

Since the end of the 1990s, the software industry has undergone tremendous changes. Driven by maturing Web service technologies and the wide acceptance of the service-oriented architecture paradigm, the software industry's traditional business models along with business strategies have already started to erode – with far-reaching consequences: software vendors turn into service providers. While traditional software products are installed at the customer site, including prepaid perpetual-use licences, so-called software-as-a-service (SaaS) or on-demand software is hosted and maintained by the service provider itself and offers usage- or subscription-based pricing models [103, 73, 72, 281]. Salesforce.com's Sales Cloud 2 is repeatedly referred to as a prime example for SaaS, mapping valuable customer relationship management (CRM) software into an online service infrastructure that can be accessed via Web browsers.[1] Exploiting the capabilities of service-oriented architectures, such services are made available "one-to-many", that is, a multitude of application instances can be run at once in a common environment. In the last decade, a large body of surveys and studies has been published which indicate the enormous potential of on-demand service provisioning. According to a series of Gartner studies, the worldwide market for on-demand enterprise applications increased by more than 25% from 2007 to 2008 (adding up to revenues of $6.4 billion) and is supposed to more than double until 2012, which will account for approximately 25% of the entire enterprise application market. SaaS is expected to exhibit consistent compound annual growth of roughly 20% through 2013 which is nearly five times the growth predicted for the total market [223, 222, 224].

The prosperous future accredited to the SaaS market by a multitude of surveys seems to turn into reality: offerings that have been in the market for several years constantly exhibit almost skyrocketing usage figures. For instance, in 2007, the bandwidth consumed by Amazon's Web service offerings such as the Elastic Compute Cloud (EC2)[2] or the Simple Storage Service (S3)[3] for the first time exceeded the bandwidth consumed by all global Amazon shopping Web sites .[4] While sales-

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[1] `http://www.salesforce.com/crm/products.jsp`

[2] `http://aws.amazon.com/ec2/`

[3] `http://aws.amazon.com/s3/`

[4] `http://aws.typepad.com/aws/2008/05/lots-of-bits.html`, accessed on 04/13/2010.

force.com reported roughly 30,000 paying subscribers in 2001, the subscription figures exploded to 1.5 million by the end of 2009.[5]

While the success story of on-demand software is likely to continue, a second wave of innovation has great potentials to shake the software industry's foundations once again. Exploiting the capabilities of Internet standards and interoperability, joint value creation of service providers has emerged. Open standards and service-oriented architectures constitute important building blocks for innovative Web service networks, tying together the competencies of specialized contributors. This development was first described in Coase's [79] seminal paper on companies' sizes. Once serving the whole value chain, celebrating what has become well-known as vertical integration, companies now focus on their core competencies. If transaction costs in the open market decrease, companies will consequently downsize: vertical integration is abandoned in favor of flexible cooperation between adaptive and lean competence-orientated partners [79, 100, 152]. In the Web service market, a multitude of small and highly specialized providers offer modular services of almost any kind. Such market structures imply that contracting out is more efficient than relying on internal transactions.

The adaptiveness of the partners coincides with the development of software customers demanding more sophisticated as well as more specialized solutions and, at the same time, longing for more flexible service provisioning [51, 100, 311, 265, 28]. One of the most powerful approaches to handle complexity is modularity, that is composing the ensemble from smaller subsystems that are designed independently, yet function together as a whole [23]. Along those lines, vendors concentrate on their core activity while leveraging knowledge and assets of complementary partners. That way, they are able to stay agile and to flexibly adapt their services to changes in the environment, be it customer-, competition-, or regulation-driven [284, 252]. Such joint value creation in terms of Web services is mostly coordinated by a mediating entity as present in today's leading service platforms: Salesforce.com offers its on-demand service market place AppExchange[6] and its development platform force.com[7], Xignite operates the Splice Mashup Platform[8], and StrikeIron has the IronCloud Web services delivery platform[9] ready, just to name a few. Recent surveys predict that such SaaS platforms will be a crucial factor for an even broader SaaS adoption [193, 102].

However, besides the above-mentioned increase in customers' demands for complex applications and the resulting agility of service providers to tackle these requirements, other concrete economic factors are driving this second innovation wave of the software industry. In this thesis, it argued that it has its seeds in the *long tail phenomenon* which was initially promoted by Anderson [9]. The original long tail story was bred by the emergence of e-business which made it possible to transfer traditional physical business to the Internet. In online stores, merchandise assortments can be displayed without the physical restrictions present in a brick-and-mortar store. What is more, Anderson [9] sees customers freed from

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[5] `https://www.salesforce.com/company/investor/financials/.`

[6] `http://sites.force.com/appexchange/apex/home/`

[7] `http://www.salesforce.com/platform/`

[8] `http://splice.xignite.com/`

[9] `http://www.strikeiron.com/Company/IronCloud.aspx`

the tyranny of compromise-ridden mass products by the possibility of pushing the niche through information and communication technology (ICT). Altogether, since customers highly value the new possibilities of accommodating specialized demand, the large amount of small sales of specialized products has the potential to overcompensate revenues generated by selling mass products.

The long tail's striking relevance for electronic services, and Web services in particular, has been largely neglected by academic literature so far. Requirements for functional and non-functional characteristics of Web services are much more pronounced and specific than in other domains. Such specificity of requirements considerably intensifies the niche effect. For instance, several goods exhibit the so-called blockbuster characteristic: The availability of highly specialized offers does not cut back the success of products that are designed to fit the mass appeal. This is certainly not true for Web services to such an extent. If the customer can choose between a Web service that perfectly fits his needs and a Web service that is programmed to capture the mass, he will most probably go for the former – if priced appropriately. However, not only the specific requirements make the long tail phenomenon important for the Web service domain. Modular services can be combined and configured into value-added complex services which have the potential to meet virtually every conceivable customer requirement, giving rise to a new level of customization. Such complex services involve the assembly and invocation of several specialized service modules offered by a multitude of expert partners in order to accomplish a multi-step business functionality [256]. Recombining service modules, new functionality is created "off-the-shelf". Beyond that, such individual composition of Web services is capable of even more: Web services are invoked more often if they provide added value in a multitude of complex services. In fact, if n services are registered with a service platform, up to $\sum_{k=1}^{n} \frac{n!}{(n-k)!}$ alternative service mashups could be created, each of them potentially meeting a specialized demand. That way, service providers can exploit economies of scope [255]: their offerings are not designed to be included in one or few complex services, but contribute to various solutions capturing diversified customer needs.

From a technical perspective, dynamic Web services are increasingly used in the context of service mashups, facilitating lightweight approaches such as RESTful architectures [126, 272] and slim messaging formats such as JSON [89]. The service mashup platform ProgrammableWeb reported that 71% of all listed APIs exposed REST interfaces by April 2010, foretelling the trend to an internet of interoperable Web services.[10] Economically, value is created through the interplay of various distributed service providers that jointly contribute to an individualized and integrated solution. However, not only partners offering complements constitute the long valley, but also substitutive services and vendors that serve the same customer segments. Thus, service providers find themselves in the fruitful state of co-opetition, breeding both complementary opportunities and competitive threats [54]. While cooperation enables advanced value creation and the access to partners' assets and knowledge [34], the competitive component diminishes adverse effects of market power and spurs improvement and innovation pressure [264, 167].

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[10] `http://www.programmableweb.com/apis`, accessed on 04/13/2010.

The above-introduced second innovation wave of the software industry (cp. Figure 1.1), most notably the combinatorics in service mashups, can be optimally catalyzed by universally accessible service orchestration platforms – service value networks (SVNs) – which are the underlying organizational form of this thesis. Thereby, optimality denotes the SVN's ability to exploit the exponentially growing number of service mashups which are offered to customers *(i)* in an automated fashion and *(ii)* via a permanently available channel.[11]

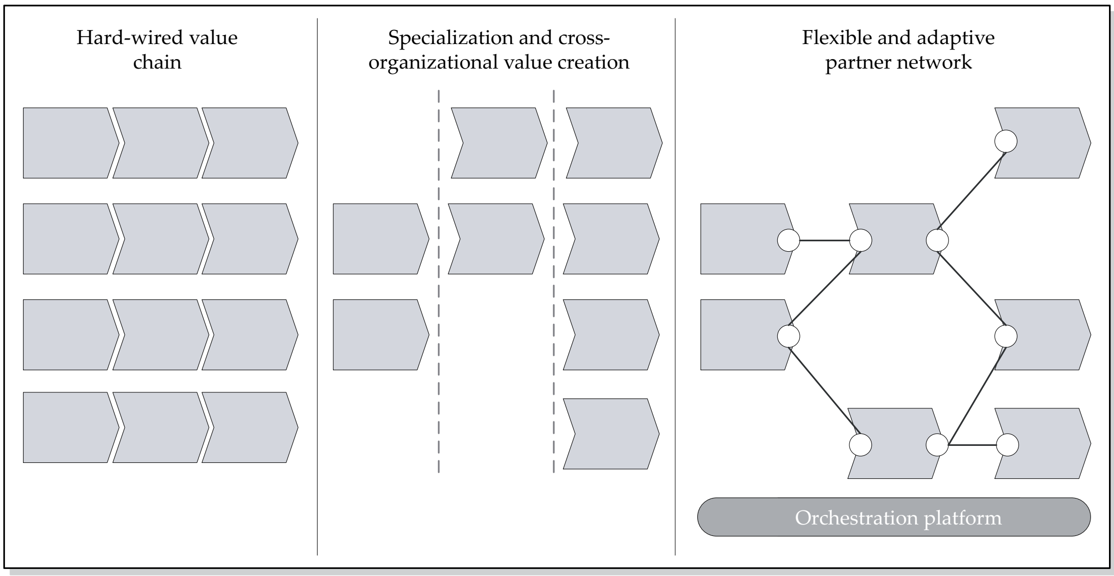

Figure 1.1: From hard-wired value chains to adaptive service value networks
Adapted from Heuser et al. [155]

While the technological side to enabling SVNs and related approaches, for instance highlighting aspects such as service engineering, service description, or service discovery, enjoys heavy research activity (cp. e.g. [344, 65, 27, 200, 318, 66, 249, 286]), economic considerations are lagging behind. Focussing on the operator of an SVN, a multitude of challenges need to be tackled when entering the market as a mediating party between service customers and service providers. New entrants to the Web service platform market have to demonstrate competitive and innovative business models. Meeting this challenge, effective strategies must include a lever to sustainably attract market participants from both sides of the markets, customers and providers. What is more, an attractive service portfolio in terms of variety and quality should be a result of the incentives given. Therefore, a certain set of objectives is to be fulfilled. Mechanism design has proven to be a powerful instrument to solve problems that involve self-interested individuals holding private information [215, 257]. In particular, auction-based approaches are ideally suited to extract distributed valuations in environments in which heterogenous services are traded [300, 262, 168].

However, only little theoretic research has been dedicated to the distinct situation of providers that are related both in cooperative and competitive terms [34]. An efficient coordination in such an environment requires schemes and measures that are particularly tailored to co-opetitive value creation.

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[11] Cp. Section 2.2.2.

1.1 Research Questions & Problem Description

In line with the research gap indicated in the previous paragraph, the core research activity in this thesis is dedicated to the design and evaluation of a scheme, or mechanism, that is tailored to coordinate the trade of complex services in newly arising service value networks, thereby capturing their characteristics and features. In SVNs, an inherent dependency of service providers can be observed, both sharing the fate of the network as a whole and directly relying on partners when offering and delivering a complex service to customers [166]. Besides the seminal contribution of Brandenburger and Nalebuff [54] that puts co-opetition on the agenda as an economic state that is worth to be analyzed, academia provides only little work that deals with application scenarios of the co-opetition phenomenon. What is more, as the importance and influence of services in today's world is constantly and irreversibly rising, insights on upcoming organizational forms driven by this development are still scarce. Therefore, the first research question of this thesis addresses the *emergence of service value networks*. In more detail, it scrutinizes *(i)* why complex services are composed by diverse providers' offerings beyond company boundaries and *(ii)* which characteristics are exhibited by organizational forms such as SVNs that breed this kind of value creation.

Research Question 1 $\prec$**CHARACTERISTICS AND EMERGENCE OF SERVICE VALUE NETWORKS**$\succ$**.** *How can service value networks be defined and which economic factors drive their emergence?*

While supporting the enablement of SVNs from a technical perspective has already gained immense research momentum with spearheads such as service description [225, 249] or (semantic) service discovery [200, 318], just to name a few, economic aspects fall behind. For this reason, Research Question 1 is addressed from an economic standpoint, first by defining Web services from an interdisciplinary perspective as the kind of services that optimally suit SVNs. The reasons for SVNs to emerge, their characteristics, and their determination for Web services are analyzed and motivated in a second step. By formalizing SVNs in a graph-based approach, an essential basis for the design of theoretic models in this domain is set.

The solution to Research Question 1 lays the foundation for defining a mechanism that is customized to the challenges imposed by service value networks. It is well-known that there is no "all-in-one" mechanism to suit any setting in any kind of application scenario [329, 240]. Therefore, designing a mechanism to facilitate the trade of complex services in SVNs requires a thorough analysis of the environment at hand. In more detail, taking over the role of a network designer, the mechanism design problem arises as participating agents act opportunistically according to their private preferences for different outcomes – which are, most probably, not in line with the system's overall goals [257]. These two conflicting fields must be brought together by a network designer, or operator, when launching a new platform.

This issue makes the transition to Research Questions 2 and 3. First, as will be shown in this thesis, mechanism design in its narrow form does not fully match the problem at hand. Classic economic objectives that are considered in mechanism design are certainly important in the context of service networks, however, miss out crucial objectives of network design, as for instance installing effective incentives for participants to join. Therefore, it is important to upgrade classic mechanism design to a *networked mechanism design perspective*. In this regard, some of the desiderata of classic mechanism design are likely to fall victim to the new objectives that shall be met in networked environments.

Research Question 2 ≺NETWORKED MECHANISM DESIGN≻. *How can classic mechanism design be mapped to networked mechanism design?*

This question will be addressed by reviewing mechanism design theory and approaches that relax certain classic assumptions as, for instance, is done in Nisan and Ronen [245], Parkes et al. [260]. In this thesis, by incorporating objectives from cooperative and network games, the scope of classic mechanism design in a narrow sense is widened to a broader understanding which will be called networked mechanism design.

Picking up this approach, it is possible to define mechanism requirements that go beyond the ones usually applied in classic mechanism design. This is also the case with the *co-opetition mechanism* that shall coordinate service providers tailored to the requirements that arise in the launch phase of a service value network.

Research Question 3 ≺MECHANISM REQUIREMENTS IN SERVICE VALUE NETWORKS≻. *Which are the design objectives of the co-opetition mechanism in order to suit the requirements of early service value networks?*

In order to define the components of the mechanism designer's goals, the third research question is tackled by a thorough environmental analysis, which includes objectives from classic mechanism design, cooperative game theory, and network games. The consideration of merely competition-oriented design goals would miss out the cooperative, value co-creating element of SVNs while an exclusively cooperation-based consideration would be likely to impinge on price and quality competition.

Each of the three research questions outlined so far in turn lead to the core contribution of this thesis – the implementation of the co-opetition mechanism based on the objectives resulting from the environmental analysis. The most important objectives originate from the network side, including incentives not only to boost network growth, but also to earn participants' commitment to remain in the SVN by not only rewarding service providers for a transaction made, but also distributing some share of the revenue to service providers that keep valuable offerings available. If payments are distributed to a superset of the allocated service providers, fairness is particularly important to adhere to. The more valuable a service provider is with respect to complex services offered in the SVN, the more vital it is for value creation, and therefore, the greater its reward should be. Moreover, the co-opetition mechanism is to reward efforts of service providers to increase their degree of interoperability. On top, some objectives from classic mechanism design need to be fulfilled: in order to make the mechanism sustainable, its operator should not subsidize it and participants must be willing to voluntarily participate. Finally, applicability requirements with respect to SVNs are to be met. Especially in an environment which enables the trading of highly specialized services, quality is said to be the main differentiator [256], that is, the mechanism shall capture the multiattribute character of services. Moreover, when composing modular Web services, their sequence determines the offered functionality.

Research Question 4 ≺IMPLEMENTATION OF THE CO-OPETITION MECHANISM≻. *How can the co-opetition mechanism be implemented to meet both requirements from network design and from classic mechanism design subject to its ability to handle multiattribute and sequence-sensitive complex services?*

Research Question 4 is addressed as follows: first, based upon the formalization of SVNs presented in this thesis, a bidding language that allows for the submission of multiattribute service inquiries and service offers is provided. It captures the multiple non-functional quality attributes and the price of a service at both customer- and provider-side. Offered service qualities and the customer's preferences are mapped via a scoring function. That way, different levels of service quality are adequately incorporated in the auction procedure – the co-opetition mechanism – which consists of an allocation function and a transfer function. While the allocation function, that is, the determination of the "winning" service components to be offered to the customer, is closely based upon classic mechanism design theory by maximizing the system's expected welfare, the transfer payments follow a radically novel approach with respect to their scope of distribution. Applying the *power ratio-based transfer function*, service providers are granted a payment that reflects their marginal contribution to all available complex services that create value for the network, no matter if allocated or not. The applied metric to measure this contribution – the *power ratio* – is based on a renowned solution concept from cooperative game theory: the Shapley value [292].

The implementation of the co-opetition mechanism is, however, only a part of what is necessary to complete the work. It is similarly important to evaluate if the proposed mechanism meets the desired requirements. Due to the different levels of granularity in respect of the mechanism's objectives, ranging from fine-grained desiderata to target settings stated in relative terms, both analytical and numerical methodologies are applied.

Research Question 5 $\prec$EVALUATION OF THE CO-OPETITION MECHANISM$\succ$. *How can the co-opetition mechanism be (numerically and analytically) evaluated regarding its properties?*

Concerning the network-related properties, some consequences of applying networked mechanism design must be paid attention to. Network-owed properties are potentially likely to differ from classic desiderata. While the latter can be formulated on a very high level of granularity, the former may also take over the characteristic of a more globally formulated target setting rather than a desideratum. In this connection and aberrant from classic mechanism design desiderata, target settings may be formulated in relative terms. Such relative verbalization requires a comparison to suitable benchmarks.

This is the case for network growth. Due to the complexity of the Shapley-style calculations, the co-opetition mechanism's ability to foster network growth, that is, to set incentives for participants to join the SVN, can only be analytically discussed to a limited extent while deeper analyses have to be made numerically. Other network design properties turn out to be provable in an analytic fashion, as for instance, the co-opetition mechanism's potential to foster interoperability. Assuming that technical interoperability is already ensured by the common standards imposed by the operator of the SVN, interconnectedness can be analyzed subject to strategic considerations.

Further, classic mechanism design objectives are partly met by construction, however, with respect to other desiderata, the complexity imposed by the various factors that determine the power ratio-based transfer function can only be tackled in a series of simulative approaches. The results of these simulations are twofold: first, considering equilibrium strategies of service providers, their expected utility is non-negative. Second, the simulations show that the co-opetition mechanism, although not being incentive compatible in an analytic sense, limits strategic behavior and is able to account for a high degree of allocative efficiency subject to realistic network scenarios.

1.2 Structure

The previously described research outline reflects the structure of this thesis. The work at hand is subdivided into four parts. Part I includes essential foundations of the networked mechanism design approach presented in Part II, which is then comprehensively evaluated in Part III. Part IV concludes the thesis and highlights future research directions.

A high-level illustration of this work's structure is shown in Figure 1.2. Chapter 1 shed light on current developments in the software industry and summarized the research questions resulting thereof. Chapter 2 establishes a common basic understanding of the term "services", in particular "Web services", as they are the actual objects to be composed, allocated, priced, and evaluated in this work. Such activities are coordinated and conducted in service value networks, which are motivated, defined, and formalized. Chapter 3 is limited to elucidate those economic foundations that directly prepare the reader for the main part of this work: mechanism design (Section 3.1) and selected concepts and approaches from cooperative game theory and network design (Section 3.2).

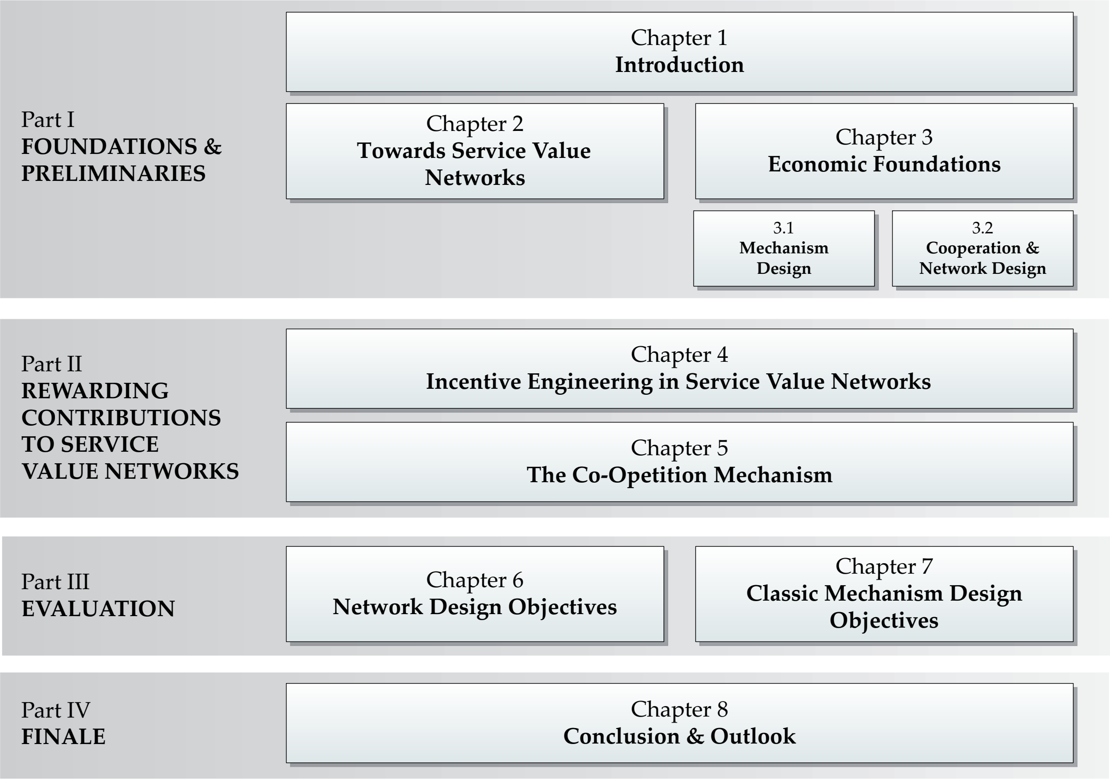

Figure 1.2: Structure of this thesis

The foundations laid in Part I open out into Chapter 4 which merges the application scenario of SVNs and the economic foundations to a networked mechanism design perspective. It prepares the introduction of the core model by elaborating requirements, highlighting the central idea of the model, and by differentiating it from related approaches. The co-opetition mechanism is introduced in Chapter 5, focussing on a bidding language for the exchange of appropriate information objects, and the mechanism implementation that consists of an allocation function and a transfer function. The chapter concludes with an overview of the algorithmic realization of the co-opetition mechanism.

In Sections 6 and 7, the postulated properties of the co-opetition mechanism are evaluated both theoretically and numerically. Chapter 8 summarizes the key contributions of this work and points to future research, limitations, and complementary topics.

Finally, note that for didactical reasons, in Part I, mechanism design as the underlying concept to this work is introduced before cooperative game theory and network design are discussed. In Part III, this sequence is reversed in order to highlight the major role of network design objectives (cp. Figure 1.2).

1.3 Research Development

Parts of this thesis were reviewed and presented at various academic conferences and workshops as well as published in the respective proceedings and in international journals. This section does not only give an overview of the published material, but also sketches the development and refinement steps that have taken place in the course of working on and writing this thesis.

An article dedicated to SVNs and their characteristics (cp. Section 2.2) was presented at the 11th IEEE Conference on Commerce and Enterprise Computing [49]. The current stage of development with respect to SVNs based on the long valley phenomenon is available on SSRN and, as an abstract, in the ERN Economics of Networks eJournal [197]. Furthermore, some considerations on the current Web service market (cp. Section 2.2.4) were accepted in the Electronic Commerce Research and Applications journal [46] and in the e-Service Journal [83].

With respect to Chapter 4, the postulated networked mechanism design perspective was accepted at the 16th Americas Conference on Information Systems [80].

The co-opetition mechanism presented in Section 5 that forms the core of this thesis was firstly presented at the 17th Annual Frontiers in Service Conference [86]. Alongside other results, a detailed description of the appropriate bidding language was accepted in the e-Service Journal [83]. The most recent version of the co-opetition mechanism was presented at the 18th Annual Frontiers in Service Conference [84] and in several other publications that also include an evaluation of certain mechanism properties [82, 85, 80]. In a shortened version, fairness properties as shown in Section 6.1 were published in the proceedings of the 1st INFORMS International Conference on Service Science [82]. A preliminary version of the considerations on interoperability (cp. Section 6.3) was presented at the 15th Americas Conference on Information Systems [81]. A paper dealing with the co-opetition mechanism's ability to foster network growth as shown in Section 6.4 was accepted at the 18th European Conference on Information Systems [85].

Furthermore, considerations on the relative power ratio as discussed in Section 8.2.2 are included in an article accepted for publication in the e-Service Journal [83].

Beyond that, between 2007 and 2010, research on SVNs and the co-opetition mechanism was contributed to and reviewed within the THESEUS program initiated by the Federal Ministry of Economy and Technology.[12] In more detail, the formalization of SVNs, the multiattribute bidding language for such environments, the co-opetition mechanism, and its evaluation in terms of network growth and fairness properties were contributed to the research project TEXO which is the part of the THESEUS program that aims at creating a platform to make modular services composable into value-added complex services and enable their trade on the Internet.[13]

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[12] `http://theseus-programm.de/en-us/home/default.aspx`

[13] `http://theseus-programm.de/en-us/theseus-application-scenarios/texo/default.aspx`

Chapter 2

Towards Service Value Networks

The current chapter's objective is to give a detailed introduction into the application scenario of this thesis – services and service value networks (SVNs). As the mechanism design approach, that is particularly tailored to service value networks, forms the main part of this work, it is of utmost importance to thoroughly discuss and define SVNs as its very foundation.

Section 2.1 discusses the general concept of a *service* from an information systems (IS) perspective. On the one hand, current economic definitions of services, mostly originating from the marketing discipline, are not clear-cut enough to transfer them to service value networks. Moreover, the definitions lack technical background. On the other hand, computer scientists have provided a bunch of definitions for (Web) services which are, however, too technical to tackle the research questions of this thesis. Based on an extensive literature overview provided in Section 2.1.1, a definition and differentiation of the terms *service*, *electronic service*, and *Web service* is given in Section 2.1.2.

Following this definition, the organizational form of *service value networks* will be introduced as a novel network type and specialization of business networks. Section 2.2 does not only contribute a fundamental definition of the SVN concept and its differentiation from related network types (cp. Sections 2.2.2), but also a thorough analysis of the environment in which SVNs evolve – Web service markets (cp. Section 2.2.1). These are, in particular, subject to some interesting characteristics that allow for an extension of Anderson's [9] well-known long tail phenomenon by the services' composition depth as a third dimension. Section 2.2.3 provides a formalization of SVNs that will serve as the notational basis for the mechanism design introduced in Part II of this thesis. Several examples for SVNs presented in Section 2.2.4 round off this chapter.

It remains to be pointed out that this fundamental chapter will address the first research question as stated in Section 1.1. Based on the service definition, this chapter discusses the economic factors that foster the emergence of SVNs and provides a clear-cut definition for this type of networked organization.

2.1 The Service Paradigm

Without any questions, services have become the major driver of value creation in the last decades. This statement manifests in official statistics showing that services make up the largest part of the gross domestic product (GDP) in industrialized countries. In 2009, the service sector's share of the GDP within the European Union amounted to 71.9% and to 76.9% in the United States.[1] As statistics show, the economic importance of the service sector increased steadily over the last years [250, 335, 30, 304]. For instance, in Germany, the GDP accredited to the service sector amounted to 67.8 % in 2007, rising to 69.3 % in 2008, and finally adding up to 72.6 % in 2009.[2] At the same time, since the 1990s, the service sector is the only sector in industrialized countries to provide growth, both in terms of the GDP and in terms of employment [122, 55].[3]

This trend is further amplified by the "servicification" of traditional products in many industries. According to Vargo and Lusch [320], the major shift towards a service-centered view is driven by changes in society and markets that lead to exchanges of services rather than goods. For instance, automobile companies enrich their products by offering additional services that round off the purchase and usage of a car, be it financial services or enhanced mobility services. For instance, BMW offers its premium service "ConnectedDrive" which provides an intelligent network of information, communication, and assistant systems to the driver, both from within the vehicle and external to it.[4] Such services are usually provided by partnering companies; in case of ConnectedDrive, the partner network includes, for instance, the news agency AFP, Google, or T-Systems, just to name a few. Generally and across industries, companies that were traditionally ranked "manufacturers" increasingly integrate services into their core product offerings. It is not only stagnant product demand in many domains, but also the customer's demand for customized and sophisticated goods which has pushed economic value downstream – away from manufacturing and toward the offering of services, both in preparing and customizing sales and in aftersales [29, 251]. Driven by advancing Web service technologies, servicification in the software industry is a fundamental trend that tremendously changes the companies strategies and business models: software vendors become service providers [103] (cp. Section 1).

The goal Section 2.1 is to provide a thorough introduction to the service concept itself as a groundwork for this thesis by defining services in general and subsequently restrain this definition to electronic services and Web services. As an exhaustive literature review will show, scholars did not yet merge economists' and computer scientists' perspectives on services, which is, however, essential to properly delimit the application scenario at hand – service value networks.

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[1] `https://www.cia.gov/library/publications/the-world-factbook/fields/2012.html`

[2] `http://www.destatis.de/jetspeed/portal/cms/Sites/destatis/Internet/DE/Navigation/Statistiken/VolkswirtschaftlicheGesamtrechnungen/Inlandsprodukt/Inlandsprodukt.psml`

[3] For a comprehensive overview on productivity and employment growth in the service sector, the interested reader is pointed to Wölfl [335], Breitenfellner and Hildebrandt [55].

[4] `http://www.bmw.com/com/en/insights/technology/connecteddrive/overview.html`

2.1.1 Related Work

Up to now, each research direction that dealt with service worked isolatedly within the bounds of a definition that suited the respective needs best. This approach led to an immense amount of diverse sector-specific definitions of "services". While computer scientists define a service based on the requirements emerging from practical implementations and, hence, focus on the technical properties of a service, they create a specification that economists cannot deal with. On the other hand, business economists put the emphasis on general properties of a service, its prerequisites, and the creation of value, thereby neglecting technical issues. In the following, an overview of existent business-related and technical service definitions is given.

2.1.1.1 Business Perspective

In spite of the large body of contributions to literature, a common definition of what a service actually is has not been agreed on yet. What is more, we do not only face different approaches to define or circumscribe services, but also entirely different philosophies.

According to Corsten and Gössinger [87], the approaches taken to explicitly define the term *service* may be divided into three classes: *enumerative definitions* that merely name examples for services, *negative definitions* that try to circumscribe services by stating what they are not, and *explicit definitions* that specify constitutive characteristics of services. In accordance with Meffert and Bruhn [220], only the class of explicit definitions is suited to establish a common basis for concise discussions and allows for an accurate derivation of implications.

Considering *explicit definitions*, three perspectives on value creation, which most service definitions are based on, can be identified: *potential-*, *process-*, and *outcome-*orientation [114]. The former focuses on the allocation of factors of production and hence comprises the *preparation* for service supply. The second dimension considers services as the activation and integration of the allocated resources, describing the *activity of resource usage* by both the service customer and the service provider, which define the invariably involved roles when services are provided and consumed. The third dimension concentrates on the *result* of this process.

In line with Engelhardt et al. [114] one needs to distinguish between *preparation* as a first phase and *delivery* as a second phase when defining a service. The first phase creates the readiness of a service provider, setting up the requirements for the immediate ability to actually deliver a service. In case of a hair cutting service, for instance, such preparation would include, inter alia, the training or hiring of staff, procurement of equipment, leasing of an accommodation, and so forth. For a Web-based service, the preparation phase includes, for instance, programming efforts and the allocation of sufficient storage and computation capacity. In more detail, the preparation phase includes general preparation activities that do not require the presence of the service customer herself or entities owned by her. At the same time, potential customers reason about the service specification that suits their needs best – in other words – they need to elicit their preferences. The delivery phase revolves around provisioning of the service by the provider and its simultaneous consumption by the customer itself or entities owned by him.[5] Additionally, further sub-phases need to be considered: typically, an *agreement* between service provider and service consumer is made before provisioning and consumption is initiated, oftentimes including *individual preparation*.[6] While the preparation phase is universal, i.e. represents the basis for every concrete service delivery, the outcome relates to a distinct delivery process. Above-introduced phases are illustrated in Figure 2.1.

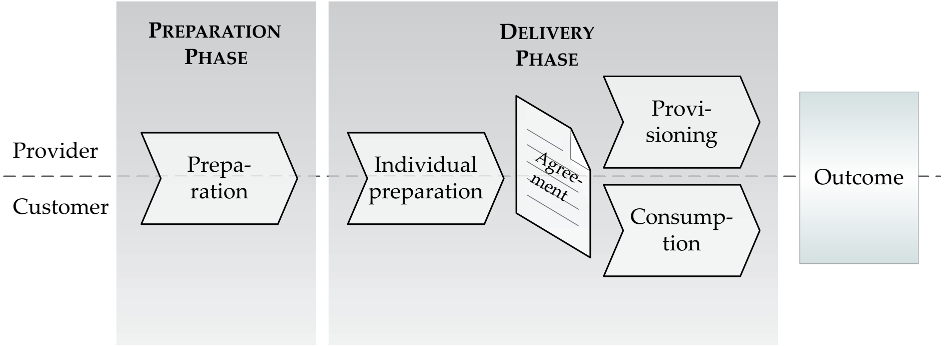

Figure 2.1: The interrelation of service preparation, delivery, and its outcome

This thesis takes the view that a potential-orientated definition of services is inappropriate since the allocation of factors is necessary in almost any value creation activity and therefore is not sufficiently distinctive. Outcome-orientation concentrates on the nature of the outcome being material or immaterial wherein, again, the essence of a service cannot be found. It is rather the delivery phase that defines the heart of a service by adequately and equally awarding importance to both the service provider and the service customer [114]. In order to prepare the service definition that underlies this thesis, a selection of the most frequently cited service definitions in academia which are focused on service delivery is presented in the following.

The *service dominant logic* is rather a philosophy than a definition. It sees services as "the application of specialized competencies (knowledge and skills) through deeds, processes, and performances for the benefit of another entity or the entity itself" [320]. This view of the service world is shared by the concept of service systems [213, 302], which are dynamic value co-creation configurations of resources. These include people, organizations, shared information (i.e. language, laws, measures, methods), and technology.

This quite encyclopedic view of services comes at the price of concreteness: the vagueness of the service dominant logic does not allow for an explicit definition of what constitutes a service. The *continuum-based approach* takes a similar line by defining dimensions to characterize services. Its key message is, however, that there is no dichotomy between products and services: a clear-cut separation of services and products is therefore not possible [297, 69, 36].

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[5] According to the uno acto principle, delivery and consumption of a service are inseparable. Please refer to the inseparability characteristic of the IHIP criteria presented in this section.

[6] Services are subject to high degrees of customization (cf. the heterogeneity characteristics of the IHIP criteria). Therefore, additional preparation in terms of customization is likely to antecede service provisioning and consumption. The more personalized a service, the greater the importance of the individual preparation included.

Another direction of impact driven by service marketing literature discusses four characteristics of services in order to *separate services from goods*. These are **i**ntangibility, **h**eterogeneity, **i**nseparability of production and consumption, and **p**erishability (IHIP criteria) [271, 270, 297, 343, 108].

Intangibility means that a service and its characteristics cannot be perceived before being bought [196, 127]. Many scholars argue that intangibility is the central difference between products and services [297]. *Heterogeneity* denotes the potentially high variability in service delivery [343]. Merging the perspective of service dominant logic to this issue, services that are performed with a particular input of specialized competencies are likely to be subject to potentially varying performance of people [270, 67, 343]. However, heterogeneity can also be interpreted as a source for providing high degrees of customization, flexibility, and variability. *Inseparability* reflects the uno actu principle which denotes the simultaneous consumption of services at their provisioning [271, 337] (cp. also Phase 2 in Fig. 2.1). It enables customers to affect or shape the performance and quality of service [139, 342]. *Perishability* circumscribes that services cannot be stored, inventoried, or transported [270, 99, 343].

The applicability of the IHIP criteria has been subject to discussion (cp. e.g. [210, 321, 110]): numerous services take some form of tangible representation (e.g. car repair, programming, etc.) and thus are not completely intangible. Also, products can be highly adapted to customers' requests and hence must be rated heterogeneous, too. Importantly, the service definition approach pursued in this thesis does not seek to differentiate services from goods, but to clearly define services in order to tie down the basis for the underlying application scenario.

A more detailed description of a service was proposed by Hill [156]. In his definition, a service denotes an activity that is performed by an economic unit B for an economic unit A, where the result of this activity is the change in condition of an economic unit C that either is or belongs to economic unit A. Additionally, the prior agreement of economic unit A is assumed. The "production of a service" is defined as the activity itself which affects persons or goods. Hence, it is not the ability to perform a task (potential-oriented definition), but rather the performance itself that constitutes the "production of a service" and therefore, the creation of value. Transferred to Fig. 2.1, Hill's [156] definition refers to the delivery phase of a service.

While specifying "traditional" services very accurately, Hill's [156] definition does not allow for a distinction of services performed on electronic data or provided via electronic networks, which is required for a more interdisciplinary understanding of services. In fact, according to Karmarkar [186], information services (which include electronic and Web services) already constitute 63% of the GDP of the US service sector.

In this vein, Gadrey [128] formulated several extensions to the definition provided by Hill [156]. He denotes "service production" as a provider B selling the right to use a technical or human capacity (resource) for a certain period to an economic unit A in order to produce useful effects on economic unit A himself or on economic units C that A owns. The use may take the form of intervention, use of technical capacity, or a human "performance". Besides being quite inapprehensible, the definition includes technical capacities, which forms a first approximation towards services performed electronically. However, technical services do not only include the provision of technical resources, but also operations on electronic data or information. Thus, the definition has to be extended and stated more precisely in order to allow not only for goods and persons to be affected, but as well for electronic resources in general to be changed.

2.1.1.2 Computer Science Perspective

More recently, with the advent of service-oriented computing and Web services, perspectives from information and computer science increasingly entered the research field of service science. Technical services do not only affect humans and goods, but also other electronic resources such as addressable data sets. From a technological viewpoint, Web services are situated on an abstraction layer above different network protocols, operating systems, and programming languages. Thus, Web services provide possibilities to expose the functionality of an application system by means of Web technologies [5].

Apart from this rather generic characterization and akin to the business-related definition, no agreement on a common definition on Web services has been made so far. According to W3C [326], a Web service is a software system that is designed to support interoperable machine-to-machine interaction over a network. Part of the definition is also an interface, which is described in a machine-processable format – in particular WSDL. Other systems must be able to interact with the Web service in a way that is prescribed by its description using SOAP-messages. The latter are transmitted via HTTP with an XML serialization in conjunction with other Web-related standards.

Berners-Lee et al. [35] supplement the definition above by concretizing that a Web service is a software service, which is identified by a uniform resource identifier (URI), exposing a public interface based on Internet standards.

The definitions sketched above may serve computer scientists' needs, but do not include important economic aspects of a service such as involved parties besides electronic resources, changes of state, and value creation.

2.1.2 Service Definition

This sections takes a constructive approach, both technical definitions aiming at the formal description of a service by means of exchanged messages, protocols, or interfaces and definitions that stress the economic aspect of services shall be amalgamated in order to introduce a general definition of services that holds for interdisciplinary service research. Until today, academia has not delivered such a definition.

Firstly, a generic definition for any kind of service is given which is followed by two specializations, namely electronic services and Web services. The latter are, again, a special case of electronic services. Based on the definition provided by Hill [156] and its extension by Gadrey [128], a *service* shall be defined as follows, thereby resorting to the general roles of a service customer and a service provider.

Definition 2.1 [SERVICE]. *A service is a set of activities performed by a provider and intended to bring about a change of state of either an entity that is owned or used by a customer or the customer itself. This change is based on a prior agreement between customer and provider which aims at a co-creation of value.*

Definition 2.1 points up the intention to change the state of an entity. Furthermore, it requires a prior agreement on the provision of the service in order to exclude unintended and unrequested acting. By co-creation of value, the contribution of both parties, service customer and provider, is emphasized. The customer's contribution can be manifold, reaching from provisioning of the entity that is changed to intensely supporting the execution of the set of activities. The provider's contribution is the performance of the activities that constitute the service provisioning. Definition 2.1 shall be able to cover any kind of service, ranging from hair cutting, to teaching or consulting, to entirely Web-based services such as, for instance, Amazon Web services.

With the rapid growth of ICT and the Web, the environment of service delivery fundamentally changed. In this context, a special kind of service emerged that is defined as *electronic service* which is accounted for in an extended definition based on Definition 2.1.

Definition 2.2 [ELECTRONIC SERVICE]. *An electronic service (e-service) is a service of which the input and outcome is provided via an electronic network.*

In more detail, a service turns into an electronic service as soon as both the input provided by the customer and the output of the service delivery take place via electronic channels. The latter can, for instance, be a telephone network or the Internet. A service that is entirely based on telephone communication is classified an electronic service just like services that are initiated and finalized via email communication or Web protocols. Note that the actual activity performed by the provider is not required to be electronic, however, any kind of interaction, as for instance follow-up inquiries that take place within service delivery, must be made via an electronic network.

As already stated in Section 1, the undergoing change in the software industry brings about on-demand services that are entirely hosted and maintained by the service provider and can be accessed via Web browsers. Due to their well-defined interface, they are interoperable with other services of that kind, being composable to meet individual customer requests. This specific kind of e-service is denoted a Web service, which requires a renewed specialization of Definition 2.2.

Definition 2.3 [WEB SERVICE]. *A Web service is an e-service identified by a URI that exposes a public, well-defined interface. Both the input and outcome is provided via a Web protocol.*

The differentiation of a Web service and the other aforementioned service types is twofold. First, the requirement of having a URI that exposes a publicly available, well-defined interface as stated in Section 2.1.1.2 must be included. A well-defined interface is not only essential from a computer science perspective, but also lays the groundwork for joint value creation in service networks (cp. Section 2.2). Second, Definition 2.2 is specialized in terms of the nature of how the input and outcome must be provided. Again, the requirement of communication via a Web protocol is a key enabler of automated service composition, which, in turn, is the driver for service value networks. Typical examples for Web services are salesforce.com's Sales Cloud 2 or the above-mentioned Amazon Web services, e.g. EC2 or S3. Yet, akin to Definition 2.2, service provisioning itself does not need to take place via communication by means of a Web protocol. A prime example for such a Web service is Amazon's Mechanical Turk[7], an on-demand scalable workforce in which inquiries and the output are standardized as in any "traditional" Web service, however, the contents that are requested are processed by humans. Figure 2.2 summarizes the definitions provided in this section.

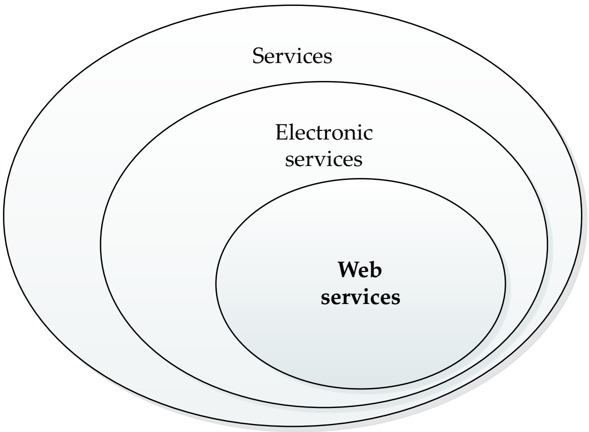

Figure 2.2: Service definitions and their interrelation

2.1.3 Conclusion

In this section, a comprehensive literature overview of service ideologies and definitions was presented, shedding light on the perspectives taken on services from different disciplines. Surprisingly, an interdisciplinary definition, looking at services from both an economic and a technical viewpoint has not been given up to now. In a constructive effort, Section 2.1.2 provided a general definition of services and derived a specialized description thereof for electronic services and for Web services by determining distinctive characteristics for each service type.

According to these criteria, which are summarized in Table 2.1, an electronic service is distinguished from a service by the transmission of input and outcome. Analogously, a Web service is an e-service with a well-defined interface and to which communication is performed via a Web protocol.

Web services – in either variation – form the basis for service value networks. Sections 2.2.1 and 2.2.2 will discuss why Web services' characteristics in this kind of environment are particularly important.

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[7] `https://www.mturk.com/mturk/`

Table 2.1: Distinctive characteristics of service types

Characteristic	Service	E-service	Web service
Input/outcome transmission	any	electronically	electronically
Interface	any	any	well-defined
Communication protocol	any	any	Web protocol

2.2 Service Value Networks

The long tail phenomenon has been heavily discussed in recent years. What has been neglected so far is its striking relevance for Web services as they are defined in Section 2.1.2. Whereas customers' expectations about information goods are often vague and transient, their requirements are more pronounced and specific when it comes to articulating functional and non-functional characteristics of Web services. Moreover, modular Web services can be combined and configured into service mashups that meet virtually every conceivable customer requirement. In this vein, the long tail phenomenon can be leveraged into a new dimension – the *long valley*, where every service exerts positive network externalities on the remaining services, thereby spurring an increase in supply and demand. The combinatorics of constructible service mashups are enabled by universally accessible service orchestration platforms named service value networks (SVNs).

The remainder of this Section 2.2 will highlight different facets of service value networks. In the following section, the reasons for service value networks to form will be deducted from current industry trends and academic advances. In Section 2.2.2, based on a thorough literature review, service value networks are differentiated from related organizational forms and their major characteristics are discussed. As we will see, management literature, social science, and computer science have developed tons of definitions for all kinds of networks. However, service value networks exhibit special characteristics compared to the known definitions that are not yet sufficiently discussed and formulated. As both academics and practitioners still lack approaches to formalize and economically analyze SVNs, this research gap is filled by introducing a formalization of SVNs in Section 2.2.3 that builds the foundation for the co-opetition mechanism. In order to support the definition of SVNs, Section 2.2.4 outlines different examples ranging from real-world SVN forerunners to efforts in research projects to a comprehensive fictional example. A conclusion in Section 2.2.5 rounds off this section by summarizing the benefits bred by service value networks.

2.2.1 Unleashing the Combinatorial Power of Service Mashups

Many niche products are available on the Internet, and customers are snapping them up.[8] For example, in their analysis of Amazon's sales patterns, Brynjolfsson

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[8] It is well-known that the Internet facilitates easy reproduction and distribution of digital goods. Constantly decreasing prices for electronic transactions made it possible to cheaply store not only popular, but also a multitude of niche products [10].

et al. [58] find that 30%-40% of sales are for books that are not commonly available in a brick-and-mortar store. This phenomenon of *selling less of more* has become known as the *long tail* [10]. It is especially pronounced for digital goods, which can be kept in stock at virtually no cost. However, Brynjolfsson et al. [59] provide evidence that the long tail phenomenon is more than just a result of decreased costs and increased supply. The factual availability of niche products can also change customer tastes: from mere exposure to products that were previously unavailable, customers start to cultivate a dedicated taste for the niche – a latent demand.

Consequently, the distribution of sold products not only has a longer tail due to the plethora of more "obscure" products being offered, but the tail is also growing "fatter" because customers are increasingly coming to like non-mainstream products [10]. In conclusion, several studies indicate that the aggregated sales volume attributed to the tail is quite substantial [58, 10, 59, 130, 57]. Putting all of these small sales volumes together, they reveal the potential to grow something big. For instance, most of the monthly sales for the online music streaming service Rhapsody[9] are for songs that are not among its top 10,000 sellers [10]. Further, AdMob Inc. [3] analyzed the ordered demand distribution of free iPhone applications in Apple's App Store and found that only 5% of the applications (116 apps) are downloaded by more than 100,000 users. Conversely, an astonishing 81% of the applications are downloaded by less than 10,000 users.

What is true for digital products also holds for electronic services. This thesis argues that the long tail effect is considerably more pronounced in the domain of Web services. Compared to products, electronic services possess at least two additional properties that are conducive to creating a long tail: *(i)* they are usually requested by service customers with *specific functionality requirements* in mind, and *(ii)* due to their modular nature, they can easily be *combined into service mashups* that have the potential to meet virtually any conceivable customer requirement.

Specific functionality requirements. Some aspects of the long tail phenomenon are disputed. In particular, critics argue that it is mitigated by the so-called *blockbuster effect*, which is commonly observed in the product domains of books, music, and movies that are often referred to in this context. The blockbuster effect is said to occur when the consumption of blockbusters, i.e. products with mass appeal and huge sales, remains robust even when more special interest products are introduced [219]. Elberse [111], for example, finds empirical support for this hypothesis in data from the Australian online DVD vendor QuickFlix[10]. Customers who buy niche movies tend to be heavy users who also go for the blockbusters. In other words, although you might have a penchant for documentaries about viniculture in Macedonia, you might still want to purchase BBC's top-selling, high-polish non-fiction about the world's most exclusive wineries. This is the snare in Anderson's [9] long tail story: blockbusters and the newly cultivated taste for niche products are not mutually exclusive. Profits made through niche products might thus be overlain by blockbuster revenues as evident in Elberse [111].

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[9] `http://www.rhapsody.com/`

[10] `http://www.quickflix.com.au/`

However, we argue in support of the long tail phenomenon that Web services are less affected by the blockbuster effect than the above-mentioned "leisure products" are. Customers of Web services expose very particular functionality requirements that are much more diversified than specifications for books, music, or movies [202, 221]. Consequently, customers will always prefer a more specialized service that closely meets their requirements over a one-size-fits-all service – if it comes at a reasonable price.[11] This taste for more specialized services fuels the long tail advocates' main argument, namely that customers suffer from the tyranny of the mainstream offerings inherent to the traditional brick-and-mortar-business [9].[12]

Specialization through service composition. In contrast to information goods, electronic services can be effectively configured and combined to form service mashups that meet even the most specialized customer demand. Mashups are complex service solutions composed of various modular service components according to the customers' requirements; this composition process constitutes a value-added and multi-step business functionality [256]. The ability to compose specialized service mashups from a set of existing services dramatically boosts the long tail idea. On the one hand, the individual services become more attractive to customers because they can be combined to create many different specialized service mashups. On the other hand, each of the available services is more attractive to customers because they can be employed in a number of specialized service mashups. Consequently, service composition enables a new generation of combinatorics that transforms the long tail phenomenon into a *long valley*. In other words, the combinatorics adds a third dimension to the long tail, thereby creating a plane (cp. Figure 2.3). Thus, the sales volume generated by a long valley-style distribution not only depends on the length of the tail, but also on the composition depth, i.e. the number of possible ways to recombine services.

In the long valley, the long tail phenomenon is dramatically amplified. First, the long valley offers a large host of specialized solutions "off-the-shelf" that are highly valued by the customer. According to a Forrester study [154], for example, customers are currently dissatisfied with the lack of customization options and dearth of specific business applications. Both shortcomings can be addressed by service composition [338].

Second, service providers will also benefit from service composition, because in addition to potentially bolstering the stand-alone appeal of their product, they might also see their services become a valuable part of a complex service. Thereby, each available service offering becomes more valuable and will be invoked more often. Service providers can therefore exploit economies of scope by contributing to various solutions that meet multifaceted demands. Unlike in other domains, it is not only the customers whose preferences give rise to network effects in SVNs. It is also, and maybe even more, the core competencies of the service providers that fuel economies of networks, in particular, economies of scope.

Third, service composition will also create network externalities that will further multiply the previous effects. As the number of available services increases, more

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[11] A detailed survey on service characteristics, especially heterogeneity, which necessitates a high degree of customization, can be found in Section 2.1.1 and in Zeithaml et al. [343].

[12] Due to physical restrictions, brick-and-mortar stores are doomed to offer a selection of mainstream products, which account for an exponentially large share of sales.

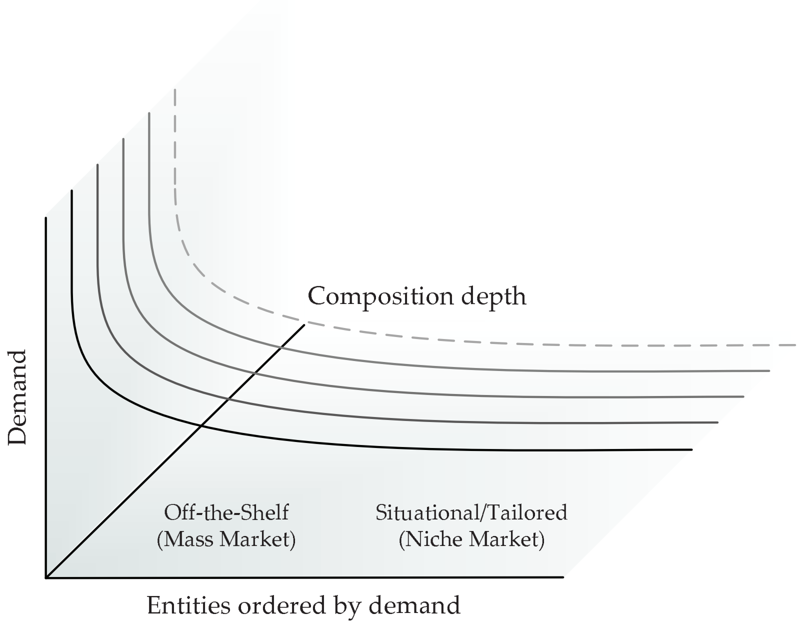

Figure 2.3: The long valley expands the long tail by adding composition depth as the third dimension

specialized service mashups can be configured. This in turn creates more customer value and thus boosts demand, which motivates service providers to offer more services, and thus the cycle begins anew. In short, service composition creates a two-sided market [62, 274, 14] in which customers appreciate the availability of more service providers and vice versa.

This trend towards more specialized, but modular service offerings is already observable. In 2007, the bandwidth consumed by Amazon Web Services exceeded the bandwidth taken up by the entire global network of Amazon.com retail websites for the first time.[13] The number of specialized, modular services on the market has continued to boom ever since. Moreover, over the course of 2009, the number of mashups listed at ProgrammableWeb[14] shot up by roughly 25% to a total of more than 4,500 composite Web services.

From a technological standpoint, complex Web services or Web service mashups came to life with the advent of Web 2.0 technologies and the renaissance of HTTP appreciation. While the first mashups were dedicated to small customer applications integrating simple data in the Web browser (e.g. RSS feeds), today's mashup technology has the potential to integrate enterprise applications. Big and RESTful Web services encapsulate functionality and put them behind clearly defined interfaces based on SOAP, WSDL, and HTTP, thereby facilitating lightweight approaches such as RESTful architectures [126] and slim messaging formats such as JSON [89]. Through extensive reuse of existing resources and simple programming models, mashups not only facilitate the ad-hoc development of highly situation-specific applications, but also boost the composition depth of complex services.

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[13] `http://aws.typepad.com/aws/2008/05/lots-of-bits.html`

[14] `http://www.programmableweb.org`

The business side of the long valley is closely connected with the technological aspects. The value for the customer is created through the interplay of complementary service providers, each of whom contributes an incremental added value to the overall complex service [51, 28]. Due to specialization, most single service providers are not able to serve a customer request without the assets of complementary partners. However, in order to keep up with innovation pressure and to alleviate the adverse effects of market power, the long valley should also contain substitutive service offerings [264, 167]. Service providers thus find themselves in the fruitful state of *co-opetition*, which breeds both complementary opportunities and competitive threats [54]. We argue that *service value networks* provide the appropriate technological and economic governance structure in which the long valley can be cultivated and prosper. SVNs support the duality of cooperation and competition, thereby driving the strategies and actions of the participants without them explicitly cooperating. The next section will reference to this argument in detail.

2.2.2 Definition & Related Concepts

When asked for a definition of a "service value network", academics and practitioners alike usually bubble over with riotous examples and visionary scenarios. The uninitiated recipient of such torrents of words consequently assumes that there must be a tacit common understanding of the concept and refrains from further questioning. However, the relevant literature has in fact failed to provide an explicit and unambiguous definition of SVNs to date (cp. e.g. [146, 71, 147, 28, 43]). Despite the relative straightforwardness of exemplary instantiations of SVNs, considerable uncertainty and disagreement on what is actually *not* an SVN remains. In an effort to map out the conceptual boundaries and formulate an explicit definition of SVNs, related concepts from organizational theory are compared, which shows that many of their features are not exclusive.

But before developing a definition for SVNs, we have to back up a bit first: Ever since the seminal work by Williamson [332], economists distinguish between markets and hierarchies as the two extreme forms of organization. *Networked organizations* are a hybrid organizational form that has gathered momentum in recent decades [226, 316, 19]. Most importantly, networked organizations combine the advantages of markets, such as flexibility, adaptability, and efficiency, with those of hierarchies, above all control and protection of knowledge and core competencies. This combination results in the following advantages:

- adaptability and flexibility while maintaining control [145, 152]
- protection of business knowledge through modularization [23, 163, 158]
- efficiency through market-based coordination [226]
- insurance against uncertainty in supply and demand [181]

The most prominent types of networked organizations are business networks [162, 143, 273], strategic alliances [95, 339], virtual organizations [134, 159], and smart business networks [324, 323, 152, 153, 60]. Clearly, SVNs should also be on this list. But what distinguishes SVNs from other organizational types in this category?

Business networks constitute the most general form of economically motivated cooperation among different firms or legal entities [162]. As in any cooperation, participation in a business network is based on the perception of mutual benefit and believed to lead to the co-creation of business value. In addition, business networks tend to be temporary, project-driven, or goal-oriented cooperations that can comprise both homogeneous (i.e. competing) as well as heterogeneous (i.e. complementary) network partners [34].

Strategic alliances and *virtual organizations* are derivatives of business networks. Strategic alliances usually denote cooperations among otherwise competing firms with the intention to share risk or achieve economies of scale [145, 231]. Virtual organizations, on the contrary, stress the formation of firms with complementary core competencies in order to achieve a goal one alone cannot master [307, 336].

Smart business networks (SBNs) refer to a new era of business networks that emphasize the *smart* use of ICT to facilitate network interaction. Smartness is in this case a relative term connoting effectiveness and a comparative advantage through the use of ICT [153]. ICT is also seen as an enabler of network agility, i.e. the network's ability to "rapidly pick, plug, and play" business processes [152]. The concept of SBNs is tightly coupled with the evolution from "mass customization" to "mass individualization", because such networks have the capability to quickly evolve on demand according to specific customer needs and requirements [60]. Moreover, after an individual request has been fulfilled, an SBN can quickly be dissolved again. These quick connect and disconnect capabilities, which enable ad-hoc joint value creation, are only possible because the firms collaborating in an SBN provide modular business capabilities. In addition, the modularity of potential network members not only allows for spontaneous network orchestration, but also provides better protection for a firm's core competencies [163]. Trust problems, which are commonly encountered in virtual organizations, are thus not as severe and the SBN may recruit members from a more open pool of potential partners [317]. The formation and coordination of SBNs is provided by one or more particular firms in the network pool. Hinterhuber [157] denotes these firms as "network orchestrators". Network orchestrator and network operator can thereby coincide. A prominent example of a smart business network orchestrator is Li & Fung[15], which coordinates a network of more than 8,000 network partners.

This review demonstrates that the same prototypical characteristics cited by the service science community to describe SVNs are also found in more general organizational concepts. For example, Hamilton [147] notes the presence of complementing and competing firms in SVNs and Spohrer et al. [302] underscore the interaction of different entities for mutual benefit; both phenomena are inherent parts of a business network. Basole and Rouse [28] additionally emphasize the role of information technology as an enabler for SVNs and highlight its importance in empowering customers as the "triggers of all activities in the network". However, these elements are also definitive for SBNs [152].

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[15] `http://www.lifung.com/eng/global/home.php`

One might also argue that SVNs are located within the service domain, while SBNs focus on products. Though SVNs do inherently have a strong service focus, this differentiation lacks teeth in that service scientists themselves tend to view products as mere "vehicles for service delivery" [320, 12]. Much more precisely and concrete, SVNs are a special case of SBNs in which the coordination and orchestration of services is performed automatically by a universally accessible network orchestration platform which itself is not necessarily technically centralized (cp. also Figure 2.4).

Definition 2.4 [SERVICE VALUE NETWORK]. *Service value networks are smart business networks that provide business value by performing automated on-demand composition of complex services from a steady but open pool of complementary as well as substitutive standardized service modules through a universally accessible network orchestration platform.*

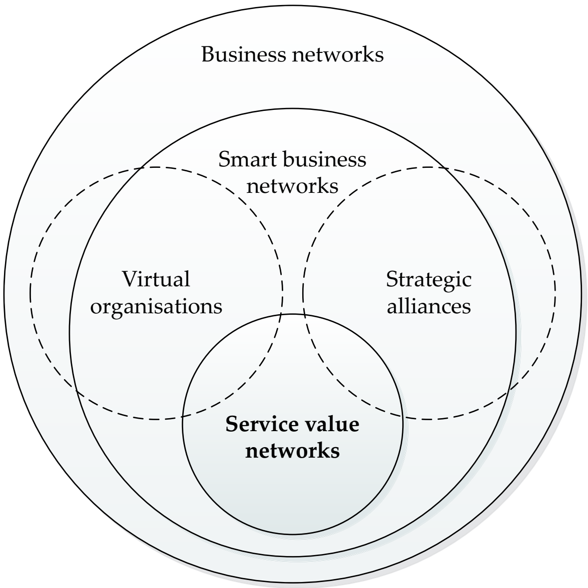

Figure 2.4: Relationship between different concepts of networked organizations

This definition is distinctive because network composition and orchestration is generally not automated in SBNs. Let us consider each part of the definition in more detail.

Complex services. A *complex service* is composed of various component services. More precisely, complex services typically involve the assembly and invocation of several component services offered by diverse enterprises in order to complete a multi-step business functionality [256]. In turn, *component services* are either other complex services or functionalities that are provided via a Web service.

Standardized service modules. Services must be plug-and-playable in order to harness the combinatorial power of service mashups, which can ultimately be used to harvest the latent demand of the long valley. This can only be achieved through service modules with standardized interfaces. Furthermore, the SVN's automated service orchestration requires that standardization encompasses the specification of acceptable parameter values in machine-readable form.

Steady but open pool of complementary and substitutive services. Services have to be (manually or automatically) registered with the service value network in order to be eligible for composition. This set of registered services forms the steady pool from which a complex service is composed. However, the registration is open for any service which meets certain minimum requirements, in particular with respect to appropriate interface specifications. It is also conceivable that the service value network itself will actively browse the service landscape for eligible services and register them automatically. In this context *steady* means that the SVN maintains a list of services (including their interface descriptions), independent of whether there is a current service composition request in the network. *Open*, however, refers to the fact that no service can be excluded from the network, as long as it meets the publicly known minimum requirements defined by the platform provider.

Automated on-demand service composition. *On-demand* refers to the network's ability to orchestrate a complex service ad-hoc and upon customer request. At the time of the request, the SVN will *automatically* search for an optimal path through its network of registered services (cp. Section 5.2.2). Optimality is thereby evaluated with respect to a goal function, for example the overall wealth of all parties involved which is known as *market efficiency*. In general, a path through the network is automatically chosen such that the economic surplus of one or more market participants is maximized. However, automating the mashup orchestration process does not only require a goal function to be specified, but also calls for a mechanism that guarantees the maximization of the goal function – as for example the mechanism presented in this thesis.

Universally accessible network orchestration platform. Finally, all of the above components are brought to life via the network orchestration platform. The platform encompasses the technical infrastructure and business logic necessary to perform market-based on-demand service composition and maintains an up-to-date list of orchestratable services. As such, the platform is the definitive interface for and between service customers and providers. Consequently, it is absolutely critical for the platform to be universally accessible and permanently available within its service domain; otherwise available services may be excluded from the platform (thereby violating the openness requirement) and business opportunities will be lost.

2.2.3 Formalizing Service Value Network

As introduced in Section 2.2.2, services must register (or be registered) with the service value network in order to be eligible for composition. The set of r registered services $\tilde{V} = \{\tilde{v}_1, ..., \tilde{v}_r\}$ forms the steady pool from which a specific, customer-driven complex service, so to say one possible instantiation of the SVN tailored to a specific customer requirement, can be composed. As stated above, services are owned by diverse service providers $\tilde{N} = \{\tilde{n}_1,...,\tilde{n}_q\}$, $q \leq r$. Therefore, formally, services expose a injective ownership function $\tilde{\sigma} : \tilde{N} \rightarrow \mathcal{P}(\tilde{V})$ that indicates which service provider offers (and thus "owns") which services registered in the SVN.

It is often useful to not consider the entire pool of services, but to restrict attention to the above-mentioned specific SVN that forms upon customer request. In other words, it is an excerpt from the overall SVN which only includes candidate pools (and thus services) that meet the functionality demanded by the customer. In the further course of this thesis, SVNs will denote both the entire network of registered service providers and concrete instances thereof that meet specific requests.[16]

The following model of a (specific customer-driven) SVN captures its characteristics stated in Definition 2.2.2 using a formal notation. An SVN is described by means of a simplified statechart model [148] and is aligned with the representation presented by Zeng et al. [344]. Statecharts have proven to be the preferred choice for specifying process models as they expose well-defined semantics and they provide flow constructs offered by prominent process modeling languages (e.g. WS-BPEL[17]) and therefore allow for simple serialization in standardized formalisms.

A service value network is represented by a directed, k-partite, and acyclic graph. Each partition represents a different functionality requested by the service customer.

Services. The set of nodes $V = \{v_1,...,v_n\}$, $V \subseteq \tilde{V}$ denotes the set of service offers that are suitable to meet the requested functionality. Two auxiliary notes, source v_s and sink v_f act as a makeshift to formalize complex services as an end-to-end connection. Therefore, these nodes are not interpreted as services in the network.

Candidate pools. According to the different service functionalities that are combined in order to constitute the demanded complex service, services are clustered into k partitions referred to as candidate pools. Substitutive services are mapped to one and the same candidate pool. The vector of all candidate pools is denoted by $Y = (Y^1,\dots,Y^k,\dots,Y^{\tilde{k}})$, $1 \leq \tilde{k} \leq n$. Y specifies the sequence $[1,\dots,\tilde{k}]$ of functional steps within a complex service. Exactly one service out of each candidate pool is required to deliver an instance of the complex service requested by the customer. Let $Y^k \subset V$ denote the set of all services that belong to the k-th candidate pool. Source and sink are not considered a separate candidate pool. However, for notational simplicity, "virtual" candidate pools $Y^0 = \{v_s\}$ and $Y^{\tilde{k}+1} = \{v_f\}$ are introduced which contain the source and sink, respectively.

Ownership of services. The set of n services is offered (and thus "owned") by a set of m service providers $N = \{n_1,...,n_m\}$, $N \subseteq \tilde{N}$, $m \leq n$. The injective ownership function $\sigma : N \rightarrow \mathcal{P}(V)$ reveals which service provider owns which services within the SVN. Vice versa, let $\bar{\sigma} : V \rightarrow N$ with $\bar{\sigma}(v_j) = n_l$, $v_j \in \sigma(n_l)$ for all $j \in \{1,...,n\}$,

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[16] The respective context should clarify the intended semantics.

[17] `http://www.oasis-open.org/committees/wsbpel/`

$l \in \{1,...,m\}$ denote the surjective function that maps any service $v_j \in V$ to its distinct owner n_l.

Links between services. An edge e_{ij} denotes an integration relationship between nodes v_i and v_j. That is, an edge between two nodes symbolizes the interoperability of the services offered as well as their providers' willingness to cooperate. Let $\tilde{E} := \{e_{ij} | v_i \in Y^{k_1}, v_j \in Y^{k_2}, 1 \leq k_1 \leq k_2 \leq \tilde{k}\} \cup \{e_{sh} | v_h \in Y^1\}$ be the set of all possible links in a k-partite graph. This set is further restricted to represent the process-oriented view by only allowing nodes between adjoining candidate pools. Therefore, let $E := \{e_{ij} | v_i \in Y^k, v_j \in Y^{k+1},\ k = 1,...,\tilde{k} - 1\} \cup \{e_{sh} | v_h \in Y^1\}$ be the set of all possible links given the set of services V.

Fully intermeshed SVN and restrictions to the set of links. Based on the notation introduced above, the graph $\hat{G} = (V \cup \{v_s, v_f\}, E \cup \{e_{hf} | v_h \in Y^{\tilde{k}}\})$ represents the fully intermeshed network including source and sink and with all theoretically allowed links between services. However, the platform operator might not be able to "force" service providers to establish links to each and every other eligible service in the network. Therefore, in practice, not all of the possible links between services are necessarily "activated". Let $V_m \subseteq V$ be an arbitrary subset of V and $E(V_m) := \{e_{ij} \in E | v_i, v_j \in V_m \cup \{v_s\}\}$ the set of all associated and reasonable edges. Thus, edges are only included if they form the incoming and outgoing edge of at least one node.[18] In this connection, let $E(v_j) \subset E(V_m)$ denote the set of incoming links that are reasonably associated to a service v_j within V_m (that is, they need to be part of $E(V_m)$).

Complex services. Of particular interest in SVNs are *complex services* as a central part of Definition 2.4 since they account for a value creating output. The possible realizations of complex services are symbolized by complete paths from source to sink. Importantly, a complex service incorporates exactly one service out of each candidate pool. v_s and v_f are formally excluded from paths due to them being not a service. Thus, $F_l := (W_l, E(W_l))$ with $W_l \in \{W \subseteq V | \forall k \in \{1, \ldots, \tilde{k}\}\ \exists_1 v_j \in W : v_j \in Y^k\}$ defines a complex service as one element of the set $F := \{F_1, \ldots, F_l, \ldots, F_t\}$ of all t complex services available.

Service configurations, costs, and prices. Each service v_j exhibits a *service configuration* $\mathcal{A}_j$ that is characterized by a vector $\mathcal{A}_j = (a_j^1, \ldots, a_j^m, \ldots, a_j^{\tilde{m}})$ where a_j^m is the value of the m-th attribute type of service v_j, thereby unambiguously defining all relevant service characteristics. $\mathcal{A}_j$ represents the quality level provided by a service and differentiates it from other services – it is therefore a major determinant of its costs and price. Let $p_{ij} := p(e_{ij})$ with $e_{ij} \in E$ denote the price for service v_j when being allocated as successor of service v_i. Incoming edges of the sink are not attached with prices since v_f is not considered a service, and therefore, can neither

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[18] This is true except for the links of services in $Y^{\tilde{k}}$. In this case, only an incoming node is required.

exhibit costs nor set prices.[19] Typically, in order to determine p_{ij}, service providers incorporate costs $c_{ij} := c(e_{ij})$ that accrue for executing their services at runtime dependent upon service v_i. It is assumed that the representation of internal variable costs reflects the service providers' valuations for their service offers being executed in different composition-related contexts.[20] Context-dependent prices can originate from different underlying costs, for instance, efforts with respect to data conversion. If, for example, some service v_j has two preceding nodes v_h and v_i, $p_{hj} > p_{ij}$ can occur by reason of increased costs c_{hj} which emerge from additional conversion expenses. Furthermore, strategic aspects can influence a service provider's pricing decision.

The formalized service value network. As a result from above-introduced notation, a specific SVN can be formalized as follows: $G := (V \cup \{v_s, v_f\}, E(V) \cup \{e_{if} | v_i \in Y^{\tilde{k}}\})$. For technical reasons, a reduced graph $\mathcal{G} := (V, E(V))$ is also defined, cutting off v_s, v_f, and $\{e_{if} | v_i \in V^k\}$. Further, let $\mathfrak{G}$ denote the set of all possible reduced graphs $\mathcal{G}$.

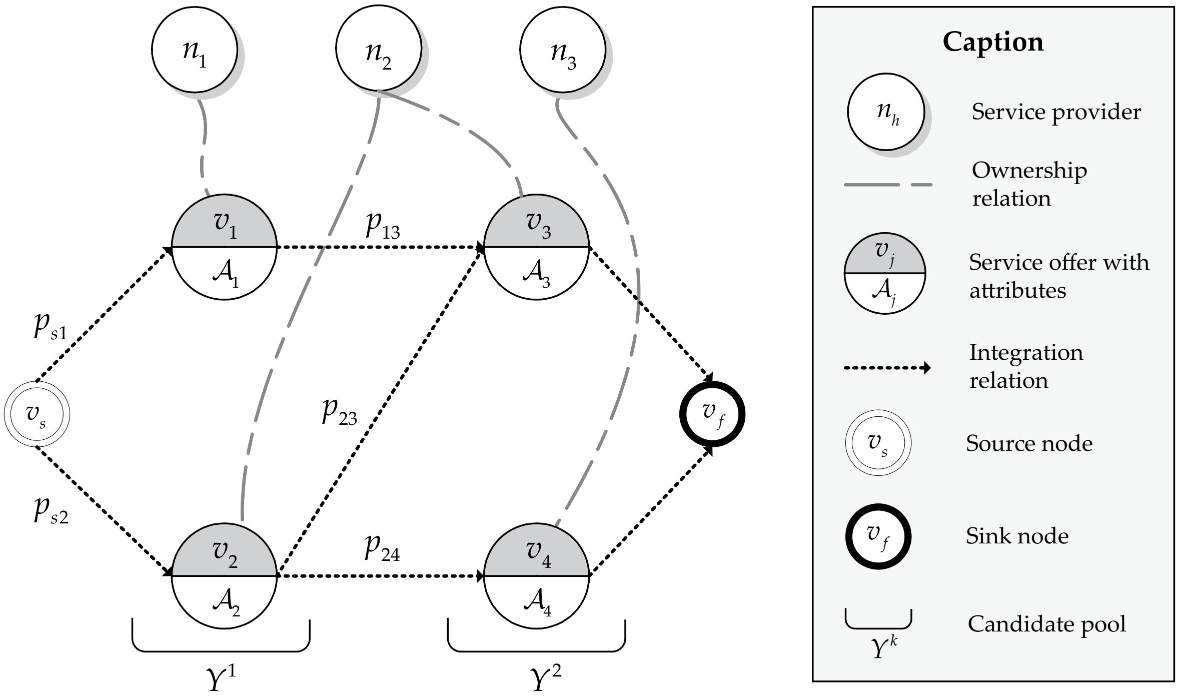

Figure 2.5: Exemplary formalization of a service value network

Figure 2.5 illustrates an exemplary formalization of a service value network with $|Y| = 2$ candidate pools which can be described as $G = (\{v_1, v_2, v_3, v_4, v_s, v_f\}, \{e_{s1}, e_{s2}, e_{13}, e_{23}, e_{24}, e_{3f}, e_{4f}\})$. Every feasible path from source to sink represents a possible realization (instance) of a complex service. There are three complex services $F = (F_1, F_2, F_3)$ in G with $F_1 = (\{v_1, v_3\}, \{e_{s1}, e_{13}\})$, $F_2 = (\{v_2, v_3\}, \{e_{s2}, e_{23}\})$, and $F_3 = (\{v_2, v_4\}, \{e_{s2}, e_{24}\})$.

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[19] Consequently, links e_{if}, $v_i \in Y^{\tilde{k}}$, are not included in E

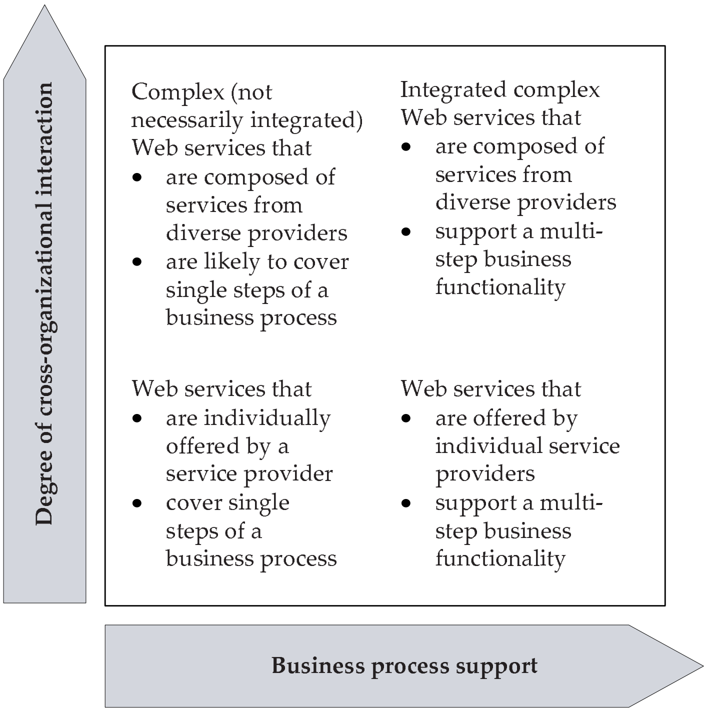
[20] The representation of a detailed cost structure of service providers is intentionally omitted, which serves a better understanding and does not restrict the generalization of the model.

2.2.4 Assessing the Value of SVNs in Practice

Now that the organizational concept of service value networks has been argued for, defined, and formally introduced, it is time to consider different implementations of SVNs. Building on the basic structure of today's Web service market, the most prominent forerunner of SVNs – salesforce.com's AppExchange – and TEXO as a current and closely related research project are discussed. Finally, a comprehensive fictional example for a complex service as it could be offered in a representative SVN, e.g. in TEXO, will be presented. This will not only help to differentiate SVNs from other networked organizational forms, but will also demonstrate the profit potential and benefits opened up by SVNs and the long valley.

2.2.4.1 The Structure of Today's Web Service Market

The current Web service market clearly points the way towards service value networks. The current market can be divided into four quadrants as shown in Figure 2.6.



Complex (not necessarily integrated) Web services that • are composed of services from diverse providers • are likely to cover single steps of a business process	Integrated complex Web services that • are composed of services from diverse providers • support a multi-step business functionality
Web services that • are individually offered by a service provider • cover single steps of a business process	Web services that • are offered by individual service providers • support a multi-step business functionality

Figure 2.6: Typology of Web services

Figure 2.6 classifies the manifestations of the Web service market by the complexity of the underlying business process and the degree of cross-organizational interaction when developing and offering services. The variety of Web services that support single steps of a process offered by individual service providers is already vast. Prime examples are services provided by Google such as Google Docs[21] as a Web-based offering to create and share work online or Google Maps[22], a map service that can be easily embedded in Web sites or service mashups. Other examples that

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[21] `http://docs.google.com`

[22] `http://maps.google.com`

enjoy high popularity are the Amazon Simple Storage Service (S3) as a simple Web service that can be utilized to store and retrieve data and the Amazon Elastic Compute Cloud (EC2) that provides resizable compute capacity in the cloud. These Web services are already extensively used in service mashups, as for instance reflected in ProgrammableWeb's composition matrix: Google Maps, for instance, is currently part of approximately 2,000 mashups listed at ProgrammableWeb while Amazon's S3 and EC2 are included in more than 100 mashups.[23]

On the other hand, applications supporting multi-step business processes are increasingly offered as Web services, too. For instance, companies like salesforce.com or Netsuite Inc.[24] 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, traditional players in the software market started to enhance their business models towards Web-based offerings. SAP's enterprise resource planning application BusinessByDesign and CRM on demand by Oracle are only two examples for the postulated shift from traditional software products to services [103]. Yet, these services are provided by single vendors.

The field of complex services that are *composed of elements provided by different vendors* is where SVNs are to be classified. Web service marketplaces such as StrikeIron and Xignite can be interpreted as SVN forerunners: they do offer a platform where service providers can market their specialized Web services to customers, yet automated mediation is not available. For instance, neither functional integration nor automatized matchmaking are provided. Added value through service composition can by created, however, both choice of an optimal combination and the actual composition is left to the customer. Salesforce.com's AppExchange goes one step further into the SVN direction, providing a market for diverse vendors to offer their complementary services to Sales Cloud 2. This network exhibits some, but not every feature of a service value network (cp. also Section 2.2.4.2). The TEXO platform as a part of the TEXO research project[25] is a current example for providing both technical and economic support for SVNs as defined in this thesis.

2.2.4.2 Real-World SVN Forerunner: AppExchange

Already being the worldwide leader in on-demand customer relationship management services, salesforce.com launched their marketplace for third party on-demand applications – AppExchange – in 2005 in order to innovate and extend their business model. The core idea of AppExchange is to offer a platform for complementary services grouped around Salesforce.com's core offering Sales Cloud 2 (formerly known as Salesforce CRM) in order to increase its value and range of covered functionalities. The bulk of services to be found at AppExchange are third-party applications offered by both freelance software developers and software companies. By May

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[23] `http://www.programmableweb.com/api/`, accessed on 05/17/2010.

[24] `http://www.netsuite.com`

[25] TEXO is one component of the umbrella research program THESEUS initiated by the German Federal Ministry of Economy and Technology. THESEUS aims at developing a novel Internet-based infrastructure to improve the usage of knowledge available on the Internet (`http://www.theseus-programm.de/en-US/home/default.aspx`).

2010, AppExchange included approximately 900 Web services to complement Sales Cloud 2.[26]

The offered services are fully integrated into Sales Cloud 2 which slashes adjustment efforts on customer side. Seamless and automated integration is enabled by the fact that all services offered at AppExchange *(i)* are deliberately built for Sales Cloud 2 and *(ii)* are based on and restricted to a proprietary but open development platform – Force.com[27]. Force.com as "platform-as-a-service" (PaaS) provides a means that allow developers to engineer applications that are pre-integrated in Sales Cloud 2 and can thus be marketed via AppExchange. Applications that are built via Force.com use the same proprietary programming language (Apex) and the same syntax to create the service's interface (Visualforce). With Force.com, an on-demand programming environment to facilitate third-party-built applications complements the portfolio offered. However, even if the customer assembles an integrated, complex service via AppExchange, single service level agreements (SLAs), billing, and a proprietary pricing scheme applies for each of the purchased component services. Pricing is thereby entirely left to the service vendors: pricing structures range from a fee per user and month bound to an annual subscription to a fixed fee per year plus additional charges that are linked to present Sales Cloud 2 users, just to name two examples. Dynamic pricing as well as a pricing at a complex service level is not available. Moreover, as one of the most important features of SVNs, automated on-demand service composition is not featured. As we have seen in the previous section, AppExchange can therefore be classified an SBN. However, the applied enabling technology theoretically allows for an extension towards an SVN.

In total, Salesforce.com's AppExchange can certainly be rated the most prominent SVN forerunner with approximately 65,000 potential customers that are given access to a multitude of third-party services that provide complementary functionality to salesforce.com's core offering.[28] Applications are offered by approximately 450 diverse vendors, which shows that the postulated trend towards highly specialized providers that rely on their core competency [23, 100, 311] has already become reality in the Web services industry: for example, in the category "project management apps", customers can find 15 Web services offered by 11 different service providers.[29]

2.2.4.3 Current Research on SVNs: TEXO

The TEXO project envisages the creation of a platform and marketplace that enables the innovation, engineering, offering, and consumption of Web services via the Internet supported by its underlying IT infrastructure. The focus of the services traded via TEXO is put upon value-added complex services that involve diverse modular service components offered by different providers. Thus, TEXO is an electronic service broker that allows for the offering and merchandizing of (complex) Web ser-

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[26] The figures were taken from `http://sites.force.com/appexchange/home/`, accessed on 05/17/2010.

[27] `http://www.salesforce.com/platform/`

[28] `https://www.salesforce.com/company/investor/financials/`

[29] `http://sites.force.com/appexchange/results?type=Apps&filter=a0L30000001Qp82EAC&sort=6`, accessed on 05/10/2010.

vices, bringing together service supply and demand. The approach is based on a service oriented architecture with its capability of exposing and connecting single Web services from different sources [27].

Figure 2.7 gives a high level architecture overview on the TEXO platform components [183]. The architecture is aligned to the fundamental modeling concepts (FMC)[30].

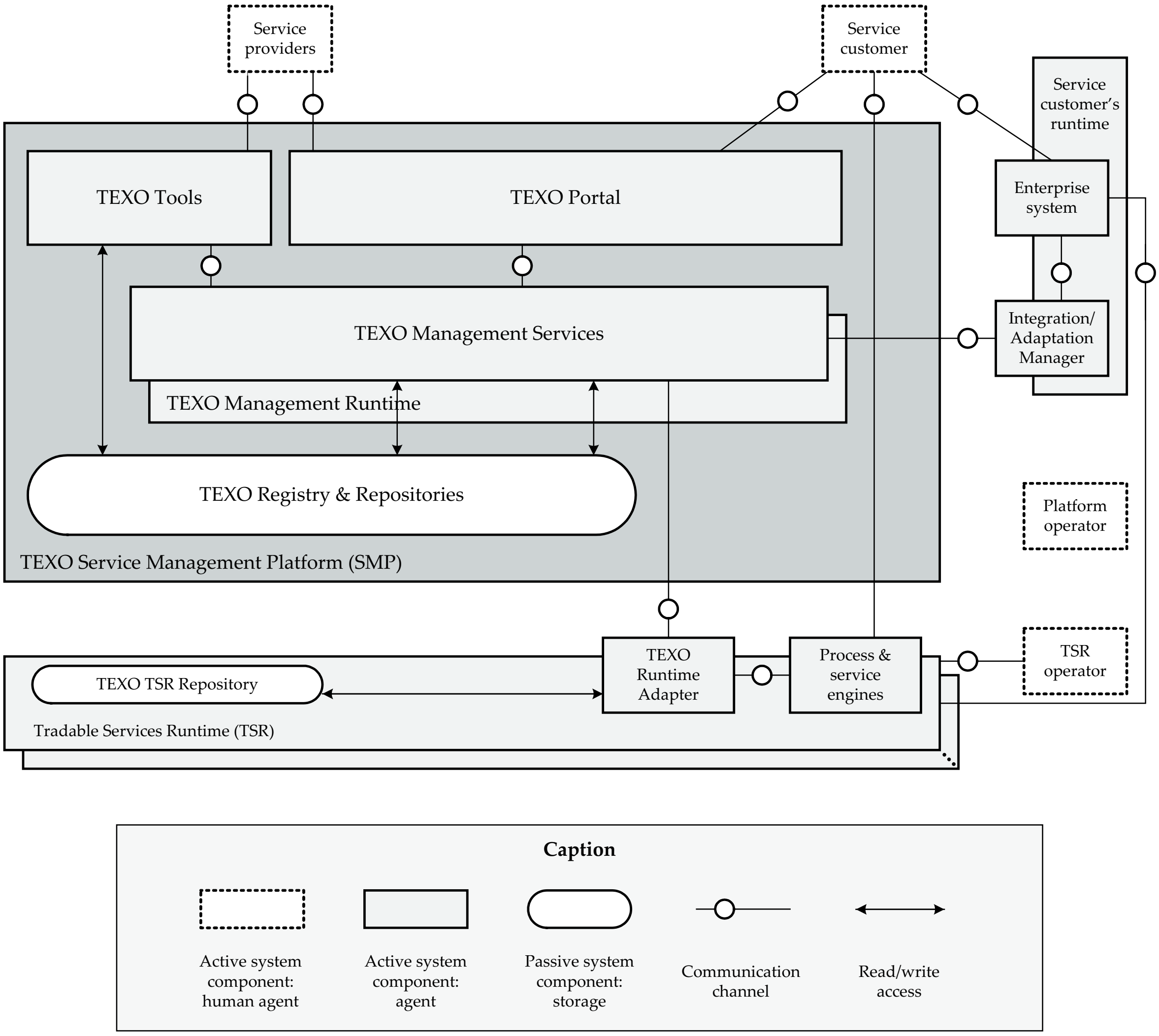

Figure 2.7: High level TEXO architecture

The TEXO Service Management Platform (SMP) as the heart of TEXO comprises TEXO Tools, the TEXO Portal, TEXO Management Services, and data storage components. The TEXO Tools include two main components: the Innovation Cockpit and the Integrated Service Engineering (ISE) Workbench. The Innovation Cockpit offers tool-based support to service innovators such as idea mining and idea evaluation tools [303]. The ISE Workbench is a service unified development environment which gives providers support in modeling, design, and description [286]. Akin to Force.com, the ISE workbench lays down the minimal requirements that must be met in order to offer (compatible) services within the platform.

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[30] `http://www.fmc-modeling.org/home`

TEXO Management Services offer core platform functionalities including service registration, service discovery, complex service auctioning, service level manager, billing, and monitoring. These services, either offered by the platform itself or by third-party providers, are deployed to the TEXO Management Runtime to be accessible by other components, and are offered to service customers and providers via a Web-based frontend – the TEXO portal. Most importantly, the TEXO Management Services allow for an automated on-demand service composition that is a required feature in SVNs. Further, a comprehensive service level management, monitoring, billing, and pricing on complex service level is facilitated.

The TEXO registry allows for a registration of tradable services on the SMP while the repositories provide and store all required information on tradable services such as their description or monitoring data.

The required input to administrate monitoring and billing of services is provided by the Tradable Services Runtime (TSR). Any service hoster can install a TSR and offer a TEXO-related hosting service. As services are usually not hosted by TEXO itself, the TEXO runtime adapter provides for an exchange of required data between the TSR and the TEXO Service Management Platform. If a service provider does not host its service itself, it can choose a TSR to deploy its service. The TEXO TSR repository of each TSR stores the information of services that are deployed on the respective TSR. Locally installed process and service engines are required to deploy different service aspects, such as service process, or user interface.

Since an automated integration of services in the customer's enterprise system is another objective of the TEXO project, TEXO offers the Integration/Adoption Manager. It is responsible for managing all integration aspects of a tradeable service into the customer's service-based application, or enterprise system, respectively [183].

The above-described architecture provides one possibility of a technical basis for service value networks which goes beyond the composition of services that are closely related to a core application as it is the case for AppExchange. In line with a service value network's characteristics, the TEXO platform is able to orchestrate a complex service on customer request with the help of the TEXO Management Services including automatized search for an optimal combination of services to be composed according to the demanded functional and non-functional customer requirements. The co-opetition mechanism elaborated in this thesis is a possible instantiation of a market mechanism that can be applied within the TEXO SMP.

2.2.4.4 Fictional Example: Complex Picture Service

Let us now turn to a comprehensive real world example which is based on currently available service offerings. Other than AppExchange and TEXO, it builds upon the ideal conception of lightweight approaches. We will revisit this issue in Section 2.2.5.

Imagine you are the chief information officer of *SizzlingNews*, a news service and editorial office, and are expected to streamline your company's business processes. Of course, as a matter of good journalism, the validity and relevance of the news events that pop into your company every day have to be investigated and assembled manually. But that is just the tip of the iceberg: the processing of a news event entails a multitude of routine tasks prior to publication. For example, assume that *SizzlingNews* usually accompanies its stories with photos. The journalist therefore needs to find and procure related pictures, store them, and add the pictures' meta information by tagging the relevant visual content. This is a tedious and highly inefficient task if done manually. Worse yet, the process delays the release of the news stories and thus severely hampers *SizzlingNews*' competitive position in the news industry.

While pondering the alternatives to doing these tasks manually, you dream of a fully automated picture-retrieval-and-tagging process realized through services that are readily available on the Internet. The images could be retrieved from photo services such as Flickr[31], Google's Picasa[32], or Yahoo!Image[33]. Web services for picture tagging are available either through crowdsourcing approaches [164], as used by Amazon's Mechanical Turk, or semantic and face recognition technologies, such as those used by ImageNotion[34] [327]. Finally, the assembled information could be stored online with Amazon S3 or other services cavorting "in the cloud" such as Wuala[35] or SMEStorage[36]. But what if you could find a Web interface capable of automatically locating and combining all of the individual services you need – in the order you need them – to form a single complex service as depicted in Figure 2.8)?

In a service value network, this is in fact possible: RESTful architectures and simplified interfaces have dramatically reduced the complexity of service composition and service description, finally enabling automated on-demand orchestration of complex services.

The previous example can also be used to illustrate the definitional boundaries of the SVN concept step by step (cp. Section 2.2.2). For instance, if instead of using a Web service, suppose you were to verbally describe your service requirements to a network coordination company like Li & Fung. The firm would then perform the mashup orchestration for you and the SVN would degenerate into an SBN. It is important to realize that fully automated service orchestration requires more than just the use of tightly integrated ICT among the network partners. Additionally, service providers have to offer modularized services and strictly adhere to predefined interfaces. Likewise, the SVN must provide a customer interface through which the service request can be formally articulated. In SBNs, however, the ability to pick, plug, and play network partners is emphasized, but not developed to the extent that network orchestration can be executed automatically.

Moreover, if the SBN was unable to combine any picture service with any storage or tagging service, it would further degenerate into a mere business network. In contrast to an SBN, the network partners in a business network are much less integrated and generally do not adhere to a common network standard with respect to the employed ICT or interface specifications. This reduces the modularity of the available services such that the alternative services cannot be flexibly interchanged

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[31] `http://www.flickr.com/`

[32] `http://picasa.google.com/`

[33] `http://images.search.yahoo.com/`

[34] `http://www.imagenotion.com/`

[35] `http://www.wuala.com/`

[36] `http://www.smestorage.com/`

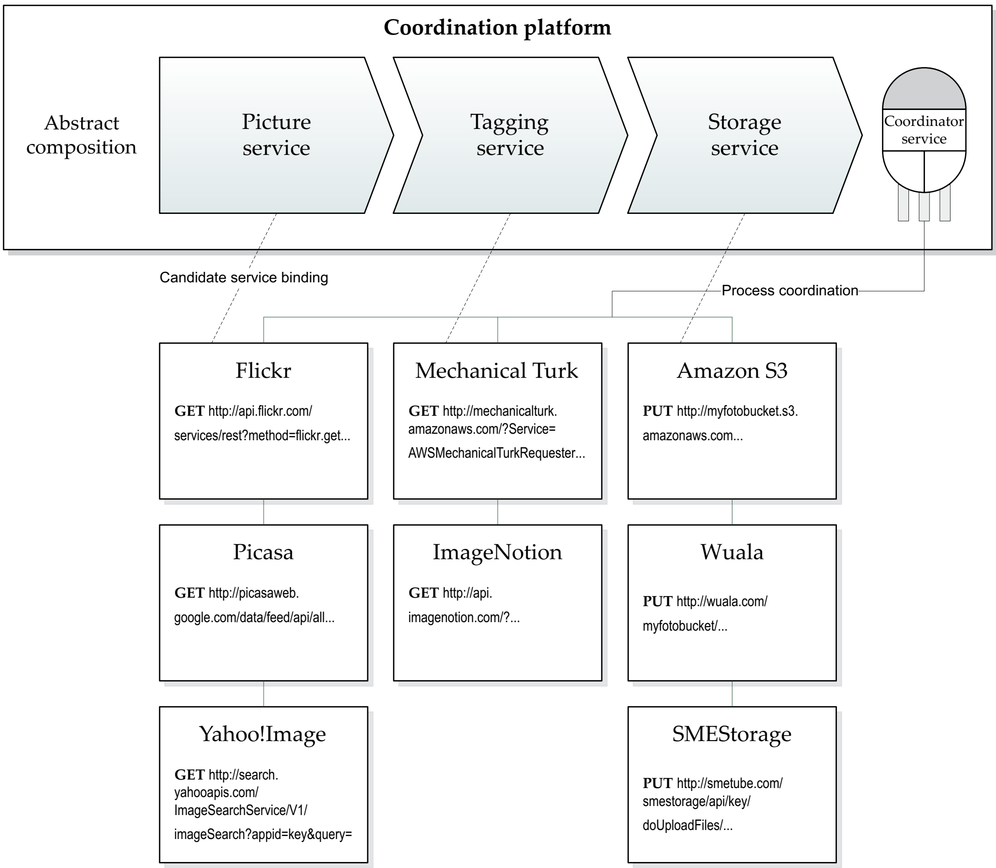

Figure 2.8: The picture-retrieval-and-tagging process as a service value network scenario

without disruption of the mashup's overall functionality. Table 2.2 summarizes the scenario variations and the resulting change in governance structures.

Table 2.2: Differentiation between network types

Network type	**Distinguishing characteristics**
Service value network	Interoperable service modules Automated service orchestration
Smart business network	Non-automated service orchestration
Business network	Non-compatible service modules

The high degree of standardization and modularization of services in an SVN is also the key to achieving the service composition depth that is descriptive for the long valley phenomenon. The long tail merely addresses the provision of all available services through one platform. In the long valley, however, any of the available services can be combined to create complex services that meet also the most specialized demand. It is important to note that the order in which the services are configured matters; different lineups can result in very different – and potentially quite useful – service mashups. For instance, invoking the tagging service first followed by the picture and the storage services could support a business process in which people or situations are tagged on pictures that are already owned by *SizzlingNews*. Thereafter, photos depicting the same event would be retrieved via Flickr and the like, and are eventually stored on Wuala. You may indeed find various re-combinations of your original service specifications to be quite useful to your company; perhaps you would also buy this new instantiation of the service mashup in order to stock up *SizzlingNews'* picture archive. In other words, the same set of services can be reordered and sold multiple times to the same customer, with each configuration addressing a different business need. In fact, if a total of n services are registered with the SVN, there potentially exist up to $\sum_{k=1}^{n} \frac{n!}{(n-k)!}$ alternative service mashups that could be sold to any one customer. This means that the number of possible service mashups grows exponentially with the number of available services, whereas the traditional long tail effect is only linear. Such is the combinatorial power that constitutes the long valley.

2.2.5 Conclusion

In Section 2.2, the economic potential of service value network was analyzed. The Web services domain was exposed to be the perfect environment for SVNs, breeding the long valley of services through the power of Web service combinatorics. In Sections 2.2.2 and 2.2.3, a definition of service value networks and their distinction from related concepts as well as a theoretical formalization were provided. Both contributions are the very foundation for designing mechanisms to automatically allocate and price complex services and to set incentives that boost SVNs in their initial phase.

The focus of this concluding section is twofold: firstly, the benefits for participants in SVNs shall be clarified. Secondly, the minimum requirements as to standards that are imposed by the platform operator shall be revisited due to differences between the ideal conception and the state-of-the-art.

Benefits for SVN participants

If you are a service consumer, SVNs can provide the service mashups that you have been looking for in vain. Earlier business applications provided over the Internet were designed to catch the average requirements of small and medium enterprises (SME), but failed to offer customization possibilities and left special requirements unsatisfied [154]. In SVNs the procurement of affordable, customized applications on demand is made possible by virtue of automated service composition. Indeed, SME tend to resort to these applications first, because they are desperate for a cost-efficient alternative to pricey on-premise software requiring large upfront investments as well as tedious do-it-yourself-solutions.[37] However, SME long for *tailored* solutions, too. Their best bet for finding these solutions are in SVNs, which exploit the power of Web service combinatorics.

If you are a service provider, you will reap the benefits of the combinatoric and network effects at play in the long valley. Your service offering can become a complementary part in multiple valuable mashups. In this way, your services will generate more value than they would as stand-alone offerings, and they are more likely to be purchased.

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[37] A survey conducted by the Sandhill Group and McKinsey & Company showed that approximately 75% of the SME polled would be ready to use some sort of on-demand software offerings [102].

Over and above those advantages, in SVNs you can become a *prosumer* [312], both enjoying the ever-expanding composition matrix that constitutes the long valley as a consumer *and* contributing to the networks' value as a provider. Your IT department can actually provide its own services in the SVN – services that were created in-house since they were not yet available anywhere else. As noted in Section 2.2.1, even the most obscure services are likely to find takers. So, each and every company's service has the potential to kiss awake latent demand.

Minimum requirements imposed by the platform operator

As stated in Section 2.2.1, Web service mashups came to life with emerging Web 2.0 technologies and the renaissance of HTTP appreciation. Typically, these service mashups as consumed today can still predominantly classified as consumer or data mashups. Consumer mashups combine data elements from diverse sources and hide them behind a simple user interface (UI). Similarly, data mashups combine data streams into a single data feed with a dedicated UI attached to it. Analyzing the top mashup tags at Programmableweb.org, it becomes obvious that the most popular mashups still belong to above-mentioned categories, with *mapping*, *photo*, *shopping*, and *video* being the top four used tags to circumscribe the mashup offered.[38] Among the most popular mashups on ProgrammableWeb.org, one finds, for instance, a mashup to help consumers locate a Nintendo Wii[39], a mashup that features live weather, forecasts, webcams, etc.[40], or a mashup that grabs sad tweets from Twitter[41] and illustrates them via pictures taken from Flickr[42].

These mashups mainly do base on RESTful Web services that encapsulate functionality and put them behind clearly defined interfaces based on HTTP, thereby facilitating lightweight approaches such as RESTful architectures and slim messaging formats. However, this is only partially true for business-oriented, enterprise mashups. While ProgrammableWeb.org increasingly lists APIs of business-related Web services that can potentially be used in mashups providing business application functionality[43], other platforms rely on minimal requirements that are a bit higher. In respect of valuable and interoperable business applications, composition is not as simple as that [330]. Both salesforce.com's AppExchange and the TEXO platform impose *open, but proprietary standards*. As shown in Sections 2.2.4.2 and 2.2.4.3, AppExchange requires services to be implemented according to Apex via Force.com; TEXO requires service providers to implement their service offerings using ISE Workbench. Both approaches enable seamless composition and compatibility of service modules from a technical point of view.

Indeed, such open but proprietary standards do not fully reflect the lightweight, ideal conception envisioned in Section 2.2.1. However, it is important to notice that

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[38] The data is taken from `http://www.programmableweb.com/mashups`, accessed on 04/05/2010.

[39] `http://www.programmableweb.com/mashup/wii-seeker`

[40] `http://www.programmableweb.com/mashup/weather-bonk`

[41] `http://twitter.com/`

[42] `http://www.programmableweb.com/mashup/sad-statements`

[43] For instance, by April 2010, approximately 80 enterprise service APIs were listed on ProgrammableWeb.org offering functionality such as CRM or IT management. These Web services are potentially available to be included in a value-added enterprise mashup.

the approaches pursued by AppExchange and TEXO do not contradict the notion of SVNs. As long as the registration is open for any service that meets the defined minimum requirements, in particular with respect to appropriate interface specifications, proprietary standards are acceptable (cp. Definition 2.4).

2.3 Summary

In Chapter 2, the first research question of this thesis, dealing with economic factors that foster the emergence of service value networks and their definition, was addressed in detail. In order to actually provide an answer to Research Question 1, some preliminary analyses were required. A thorough distinction of different service types provided a definition for Web services as the kind of service that is required in service value networks. In a further analysis, the Web services' potential to extend the long valley by a third dimension, namely composition depth, was discussed. Services in general, though so far neglected when promoting the long tail, actually amplify this effect since customers will usually prefer a more specialized service that closely meets their requirements over a one-size-fits-all service. This is not necessarily the case in (leisure) products such as books, movies, or music.

While the former argument applies for any kind of service, specialization through service composition is unique to Web services. Web services bring about the possibility of automated on-demand composition to complex services and feature modularity as well as well-defined interfaces. Moreover, by their transmission via a Web protocol, provisioning of business value can take place via a universally accessible network. Automated on-demand composition through a universally accessible orchestration platform is the distinguishing factor for SVNs, as shown in a comprehensive overview on related networked organization forms.

In order to back up the definition of SVNs, different examples were given, illustrating both already implemented forerunners of service value networks and current research endeavors. Additionally, a formalization of SVNs according to their definition was presented in order to build the groundwork for the mechanism design that will yield the main contribution to this thesis.

Chapter 3

Economic Foundations

In the preceding chapter, the situation of co-opetition was introduced as a key feature of service value networks. Certainly, there is an inherent non-cooperative element to be found in SVNs due to substitutive service offerings from competing service providers. However, service providers cannot solely act non-cooperatively: as described in Section 2.2, complex services are delivered by more than one vendor in the majority of cases. Service providers are required to cooperate with other members in the SVN, that is, their services need to interoperate with complementary offerings in order to fulfil a customer's request (cp. Section 2.2.3). A strictly non-cooperative consideration of such interaction would countervail the ecosystem-like character of SVNs. In this vein, solution concepts and ideals from both non-cooperative and cooperative game theory have to be considered, thereby taking account of the networked environment at hand. These concepts shall be the basis for the coordination mechanism and its evaluation presented in Parts II and III of this thesis.

In Sections 3.1.1 and 3.1.2, mechanism design as the basic applicable concept from non-cooperative game theory is introduced. It follows the approach of determining which rules a non-cooperative game needs to exhibit in order to achieve a certain preferred outcome. Design desiderata, that is, properties of such a preferred outcome, are outlined in Section 3.1.3. While Section 3.1.4 states impossibilities and variants of classic mechanism design, Section 3.1.5 bridges the gap between desirable economic properties and requirements yielded by computer science. However, as explained above, cooperative games and network games play a crucial role in SVNs. Section 3.2.1 gives an overview of value distribution approaches in cooperative and network games. Network formation as an important aspect in SVNs is discussed in Section 3.2.2. Section 3.2.3 continues with outlining desired properties of solutions in cooperative and networked environments.

Note that the contents in this chapter are kept domain neutral whenever possible in order to retain its character as a primer on mechanism design and cooperative game theory. That way, this chapter may also be useful to other domains that underly similar networked economics.

3.1 Mechanism Design

The discipline of mechanism design focuses on implementing a preferred system-wide solution to a decentralized optimization problem where self-interested agents act according to their private preferences for different outcomes [257]. The agents' private information cannot be verified by some central institution such as a market or platform operator that seeks to achieve certain objectives [169]. Therefore, the goal pursued cannot be solved directly. One has to design a mechanism which establishes a set of incentives, for instance, via side payments to effectively coordinate participants and to eventually enforce the system-wide solution [245]. Such side payments shall compensate the agents for potential individual disadvantages that arise if the desired result occurs. In other words, the challenge of mechanism design is to implement institutional rules which determine decisions as a function of the information known by the individuals in the economy, thereby ensuring desired events to occur even if participants act strategically in order to maximize their individual utility [237].

Classic mechanism design originates from the seminal contributions provided by Vickrey [325], Clarke [77], and Groves [140], that are namesake to the prominent class of Vickrey-Clarke-Groves (VCG) mechanisms. Such VCG mechanisms focus on enforcing truth-telling. In truthful mechanisms, all agents are incentivized to reveal their true type as an equilibrium strategy (cp. also Definition 3.12). As outlined later in this section, classic mechanism design *in the narrow sense* induces truth-telling. Yet, as will be shown in Section 3.1.4, mechanism design *in the broader sense* also values desiderata other than truthfulness.

3.1.1 Basic Concepts and Definitions

By modeling the interaction of individual agents and determining their strategy spaces, mechanism design is a sub-field of game theory [257]. The latter can roughly be circumscribed as the study of multi-person decision problems [132]. In order to introduce the basic concepts of mechanism design, a primer on fundamentals of game theory is provided in the following.

As stated above, game theory deals with decisions made in a system that includes a multitude of agents. Agents can be persons, organizations, or technical systems. Regardless of whether an agent is human or not, rationality is a basic assumption: agents want to maximize their own profits. Each agent $i \in I$, $I = \{1, \ldots, n\}$, is endowed with possibly different preferences for different outcomes of a game. The game itself can be interpreted as a set of rules according to which agents can act [292]. The type of an agent denotes its private information relating to its preferences with respect to possible outcomes of the game [169].

Definition 3.1 [Type of an agent]. *The type $\theta_i \in \Theta_i$ of an agent $i \in I$ determines agent i's preferences for different outcomes $\tilde{\eta} \in \tilde{\mathrm{H}}$ of a game, where Θ_i denotes the set of possible types and $\tilde{\mathrm{H}}$ stands for the set of all potential outcomes. $\theta = (\theta_1, ..., \theta_n)$ denotes the vector of types of all n agents.*

Based on its type, an agent will make decisions on how to act in a game. This is referred to as an agent's strategy

Definition 3.2 [STRATEGY OF AN AGENT]. *An agent's strategy* $\omega_i(\theta_i) \in \Omega_i$ *is a decision rule that defines an agent's choice of action dependent on every possible state of the game, where* Ω_i *denotes the strategy space that is at agent i's command.*

Oftentimes, dependency upon an agent's own type is sufficient. However, an agent's strategy can additionally depend upon the strategies $\omega_{-i} = (\omega_1,...,\omega_{i-1},\omega_{i+1},...,\omega_n)$ of the other agents, or i's belief of what the other agents' strategies are, respectively. Using ω_i, this dependency is intentionally left implicit in the following. Let further $\omega = (\omega_1,...,\omega_n) \in \Omega = (\Omega_1,...,\Omega_n)$ denote a strategy profile played be the n agents at hand. If we now zoom out to the overall game whose rules define the set of valid agents' strategies and possible outcomes, we can formulate an agent's individually experienced utility as a function of the outcome of the game which, in turn, results from the agent's set of strategies and the strategies played by all other agents.

Definition 3.3 [UTILITY FUNCTION]. *The utility of an agent i for the outcome* $\tilde{\eta}$ *of a game, which results from the agent's type* θ_i*, its own selected strategy* ω_i*, and the strategies* ω_{-i} *chosen by each of the* $n-1$ *remaining agents other than agent i, is denoted by* $u_i : \Theta \times \tilde{\mathrm{H}} \rightarrow \mathbb{R}$ *with* $u_i(\theta_i,\tilde{\eta}) = u_i(\theta_i,\omega_1,...,\omega_n)$.

Thus, a relation $u_i(\theta_i,\tilde{\eta}) > u_i(\theta_i,\tilde{\eta}')$ indicates that an agent i of type θ_i prefers an outcome $\tilde{\eta}$ (which is generally triggered by the decision ω_i made by i and the strategies ω_{-i} of the other agents) over a different outcome $\tilde{\eta}'$.

In the remainder of this thesis it is assumed that agents exhibit quasi-linear preferences and, therefore, have a quasi-linear utility function. This is a common assumption in game theory [215, 257, 296]. Applying quasi-linear preferences, an agent's utility transfers to a valuation where the set of outcomes can be reduced to a set of discrete choices. In more detail, the utility can be decomposed into a valuation for the outcome η from a discrete choice set H measured in terms of money, and into a (monetary) payment t_i for each agent $i \in I$. These components are linearly related.

Definition 3.4 [QUASI-LINEAR UTILITY]. *Assuming a quasi-linear utility function of an agent i and some side payment* t_i *granted to i by the mechanism if* $t_i > 0$*, or paid by i to the mechanism if* $t_i < 0$*, i's utility can be split into its valuation for the outcome* $\tau_i(\theta_i,\eta)$ *and its payment* t_i *such that* $u_i(\theta_i,\eta,t_i) = \tau_i(\theta_i,\eta) + t_i$.

By referring to $\tau_i(\theta_i,\eta) + t_i$, it is implicitly assumed that agent i is risk neutral and that the slope of i's *value-for-money curve* is not only linear, but also normalized to 1, denoting that i's utility for different choices can be directly expressed in monetary units, for instance, Euros [296]. Furthermore, this configuration is assumed to be identical for every $i \in I$, which implies that agents exhibit transferable utilities.[1]

3.1.2 The Social Choice Function and its Implementation

A mechanism operator finds itself in a situation where participants act opportunistically and hold private information on their types which cannot be extracted directly. Therefore, the mechanism operator does not only have to define its very goal, but also needs to specify the framework, i.e. the rules, of the game at hand.

In a first step, the system-wide goal is defined via a social choice function. It is to select a desired outcome (or choice in a quasi-linear setting), given the types θ of all n considered agents, that meets the (howsoever selected) favored properties reflecting the ideal of the mechanism operator [257].

Definition 3.5 [SOCIAL CHOICE FUNCTION]. *Given the agents types* $\theta = (\theta_1,...,\theta_n) \in \Theta = (\Theta_1 \times ... \times \Theta_1)$*, a social choice function* $f : \Theta_1 \times ... \times \Theta_n \rightarrow \mathrm{H}$ *chooses the system-wide preferred goal* $f(\theta) \in \mathrm{H}$*.*

In a second step, certain rules of the game at hand need to be defined. Such rules are called the *mechanism* and determine the outcome of the game given the strategies of the agents. In more detail, the mechanism is an *outcome rule* which is composed of an *allocation or choice function* $o : \Omega \rightarrow \mathrm{H}$ and a *transfer or payment function* $t : \Omega \rightarrow \mathbb{R}^n$. The allocation rule defines the distribution over choices given the agents' strategies while the transfer rule determines the (monetary) payments made to or by the agents. Note that the mechanism can only be decomposed into allocation and transfer rule if we assume quasi-linear preferences.

Definition 3.6 [(QUASI-LINEAR) MECHANISM]. *A (quasi-linear) mechanism* $\mathcal{M} = (\Omega_1,...,\Omega_n,m(\omega))$ *is defined by an outcome rule* $m(\omega)$ *which is split into an allocation function* $o : \Omega_1 \times ... \times \Omega_n \rightarrow \mathrm{H}$ *that maps agents' strategies to a choice* η*, and a transfer function* $t_i : \Omega_1 \times ... \times \Omega_n \rightarrow \mathbb{R}$ *with* $t(\omega) = (t_1(\omega),...,t_n(\omega))$ *that determines the payment made or received by all agents* $i \in I$*.*

Direct-revelation mechanisms are a special, easy-to-handle form of mechanisms, in which agents directly claim their preferences as a strategy. That is, the strategy of an agent is to declare a type $\tilde{\theta}_i = \omega_i(\theta_i)$, either truthful or not, based on its actual private preferences θ_i [257, 199].

Definition 3.7 [DIRECT-REVELATION MECHANISM]. *A direct-revelation mechanism* $\mathcal{M} = (\Omega_1,...,\Omega_n,m(\omega))$ *restricts the possible set of strategies to* $\Omega_i = \Theta_i$ *for each agent*

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[1] At full length, the definition of the payment is made via an agent-specific function, i.e. $u_i(\theta_i,\eta,t_i) = \tau_i(\theta_i,\eta) + \tilde{g}_i(t_i)$. The curvature of $\tilde{g}_i$ gives the risk attitude of i, which specifies the value-for-money coherency. In general, $\tilde{g}_i$ can be defined as an individual function for each agent. The simplifications made in this thesis are a common and reasonable assumption in game theory, especially when the amounts of money exchanged are moderate [257, 296].

$i \in I$. The mechanism's outcome rule $m : \Theta_1 \times ... \times \Theta_n \rightarrow \mathrm{H}$ is merely based on the reported types $\tilde{\theta} = (\tilde{\theta}_1, ..., \tilde{\theta}_n)$ of the agents.

Auctions are a typical example for mechanisms: in an auction setting agent i's strategy space could be the possible bids that can be submitted according to the rules of the auction. An outcome rule would specify the receiver of the auctioned object and payments to be made by the bidders as a function of the submitted bids [169]. In case of non-iterative auctions, agents are asked to state their types as strategies – this is the definition for a direct-revelation mechanism. However, this is not always the case as, for instance, in English auctions, where open bids are repeatedly submitted to the auctioneer. Thus, the agents' strategies are more complicated, as they are a function of the agents' private preferences.

In a third and last step, mechanism design brings together the defined system-wide goal (cp. Definition 3.5) and the allocation as well as the transfer function of the mechanism. A mechanism $\mathcal{M}$ is said to implement the social choice function $f(\theta)$, if the outcome $\eta^* \in \mathrm{H}$ of the game as a result of equilibrium agent strategies is a solution to the social choice function for all $\theta \in \Theta$ [257].

Definition 3.8 [MECHANISM IMPLEMENTATION]. *A mechanism $\mathcal{M} = (\Omega_1, ..., \Omega_n, m(\cdot))$ implements a social choice function $f(\theta)$, if $m(\omega_1^*(\theta_1), ..., \omega_n^*(\theta_n)) = f(\theta)$, where $\omega^* = (\omega_1^*, ..., \omega_n^*) \in \Omega_1 \times ... \times \Omega_n$ is an equilibrium solution to the game (induced by $\mathcal{M}$).*

The underlying equilibrium concept can be variable, for instance, a Bayesian Nash equilibrium or a dominant-strategy equilibrium. The Bayesian Nash equilibrium is a reasonable concept in the context of mechanism design as it assumes a common prior about the agents' type distribution. Therefore, the equilibrium strategy of an agent is a best response to the distribution over the strategies of the other agents [257]. Dominant-strategy equilibria are a very strong solution concept since every agent has to have a clearly defined strategy no matter what the other agents do. Yet, the strict properties required by dominant strategies limit the set of situations where they actually exist [168]. For a detailed definition and discussion of these and more solution concepts, the interested reader is pointed to Mas-Colell et al. [215].

3.1.3 Classic Mechanism Design Objectives

After having defined the elementary modules of mechanism design, the properties of a mechanism as classically consulted in mechanism design can be outlined. Per se, mechanisms themselves do not expose these properties. However, a mechanism has a certain property if it implements a social choice function with this property [257]. Economic requirements, or oftentimes called *ecomomic desiderata* of a mechanism, are introduced in the following Definitions 3.9 to 3.11 based on Mas-Colell et al. [215] and Parkes [257].

Definition 3.9 [ALLOCATIVE EFFICIENCY]. *A mechanism is allocatively efficient if its social choice function always selects a choice* $\eta^* = g(\theta) \in \mathrm{H}$ *such that there is no other choice* $\eta' \in \mathrm{H}$, $\eta^* \neq \eta'$, *which yields a higher valuation for all agents:*

$$\sum_{i \in I} \tau_i(\eta^*, \theta_i) \geq \sum_{i \in I} \tau_i(\eta', \theta_i) \forall\, \eta' \in \mathrm{H} \tag{3.1}$$

Put differently, $g(\theta)$ is allocatively efficient if η^* maximizes the total valuation over all agents. Therefore, allocative efficiency is also called *welfare maximization*. In this connection, it is important to note that $\tau_i(\cdot)$ stands for the true valuation, not for the agents' declared valuations. As quasi-linear preferences are assumed, it is sufficient to sum up the valuations instead of the utilities since valuations for different $\eta \in \mathrm{H}$ can be traded off against transfers. Including the mechanism operator as a further agent that values money linearly and is indifferent between the mechanism's choices, it can be shown for quasi-linear settings that any efficient outcome must allocate the same choice, however, may differ in how the transfers $t(\cdot) = (t_1(\cdot), ..., t_n(\cdot))$ are distributed [296].

Allocative efficiency as a design goal is not always desirable, e.g. if the objective is to maximize the auctioneer's revenue. In this case, the mechanism design problem is reformulated as an optimization problem which maximizes the utility of a particular agent [235, 257, 91].

Definition 3.10 [BUDGET BALANCE]. *A mechanism is budget balanced if no outside payments are required to realize the outcome rule. In addition, the net transfers between the agents for all types* θ *need to be zero:*

$$\sum_{i \in I} t_i(\theta) = 0 \tag{3.2}$$

Thus, budget balance denotes a situation in which the amount of money available in the system is redistributed, yet remains unchanged after the outcome has been determined. If net transfers can be made from agents to the mechanism (but not the other way round), we refer to *weak budget balance*.[2]

Definition 3.11 [INDIVIDUAL RATIONALITY]. *A mechanism is individually rational if it implements a social choice function that makes sure that agents are not worse-off by participating than by waiving participation:*

$$u_i(f(\theta_i, \theta_{-i})) \geq u_i'(\theta_i) \forall i \in I, \theta_i \in \Theta_i \tag{3.3}$$

where $u_i'(\theta_i)$ *denotes agent i's outside option, that is, its utility in case of non-participation in* $\mathcal{M}$.

For simplification, the utility $u_i'(\theta_i)$ of an agent's outside option is oftentimes assumed to be zero. In this case, individual rationality denotes that the agents do

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[2] One can also distinguish ex ante and ex post budget balance. In case of *ex ante budget balance*, the net transfers to $\mathcal{M}$ are balanced in expectation for a distribution over agent preferences.

not suffer any loss by participating. Therefore, this property is also called *voluntary participation*. *Ex interim individual rationality* replaces the agents' (absolute) utilities by their expected utilities $\tilde{E}(u_i(\cdot))$, which means that agents exhibit some common prior about the distribution of agents' types.

As mentioned in the introduction to Section 3.1, a central element of classic mechanism design *in the narrow sense* is the question of how to incentivize agents to reveal their private preferences (i.e. types) truthfully. If agents shall be prevented from concealing their true type, a mechanism needs to be compatible to the incentives of the agents [165]. Such *incentive compatibility* is said to be the key to overcome selfish behavior. Obviously, incentive compatibility is a concept for direct-revelation mechanisms. Rational agents will only choose the strategy of reporting their type truthfully to the mechanism if and only if their own utility is maximized in doing so.

Definition 3.12 [INCENTIVE COMPATIBILITY]. *A mechanism is incentive compatible if it is a direct-revelation mechanism in which the equilibrium strategies* $\omega^* = (\omega_1^*(\theta_1),...,\omega_n^*(\theta_n))$ *reveal the agents' true private types, i.e.* $\omega_i^*(\theta_i) = \theta_i$ *for all* $i \in I$.

As stated in Section 3.1.2, incentive compatibility can be considered at different levels of equilibria. If truth revelation is a dominant strategy, agents want to reveal their true type no matter which strategies are played by other participants.

Definition 3.13 [STRATEGY-PROOF MECHANISM (INCENTIVE COMPATIBILITY IN DOMINANT STRATEGIES)]. *A mechanism is strategy-proof if it is a direct-revelation mechanism in which truth-telling is a dominant strategy for all agents* $i \in I$. *There is one dominant strategy* ω_i^* *for all* $\theta_i \in \Theta_i$ *and for any* ω_{-i}, *such that the following equation holds for all other possible strategies* $\omega_i \in \Omega_i \setminus \{\omega_i^*\}$ *available to agent* i, $\omega_i^*(\theta) \neq \omega_i(\theta)$

$$u_i(\omega_i^*(\theta),\omega_{-i}(\theta),\theta_i) \geq u_i(\omega_i(\theta),\omega_{-i}(\theta),\theta_i) \tag{3.4}$$

Such *incentive compatibility in dominant strategies* is also a desirable property of a mechanism in terms of its complexity. Agents do not have to reason about other agents' strategies since every agent decides to reveal its true induced by its own self-interest regardless of ω_{-i}^* [257]. Therefore, the agents' strategy spaces are considerably simplified. However, incentive compatibility can also be defined in other equilibrium concepts such as Bayesian-Nash where agents exhibit a common prior belief about the other agents' distribution of types.

Definition 3.14 [BAYESIAN-NASH INCENTIVE COMPATIBILITY]. *A mechanism is Bayesian-Nash incentive compatible if it is a direct-revelation mechanism in which truthful revelation of private types is a Bayesian-Nash equilibrium strategy for all agents* $i \in I$. *A strategy profile* $\omega_i^*(\theta_i)$ *is a Bayesian Nash equilibrium strategy if for all* $i \in I$, $\theta_i \in \Theta_i$, $\omega_i^*(\theta_i) \neq \omega_i(\theta_i)$:

$$\tilde{E}\left(u_i(\omega_i^*(\theta_i),\omega_{-i}(\theta),\theta_i)\right) \geq \tilde{E}\left(u_i(\omega_i(\theta_i),\omega_{-i}(\theta),\theta_i)\right) \tag{3.5}$$

with $\tilde{E}(u_i(\cdot))$ denoting the expected utility over the distribution of agents' types.

In other words, in an Bayesian-Nash incentive compatible mechanism, revealing its preferences truthfully maximizes every agent's expected utility in equilibrium (with every other agent) [257].

3.1.4 Impossibilities & Non-Incentive-Compatible Mechanisms

The mechanism properties stated in Definitions 3.9 to 3.14 are partially interdependent and conflicting. Microeconomic literature offers a multitude of strong theoretic results showing that it is impossible to achieve certain combinations of economic design desiderata. Certainly, the Myerson-Satterthwaite impossibility theorem [239] belongs to the most frequently cited ones.

Theorem 3.1 [MYERSON-SATTERTHWAITE IMPOSSIBILITY THEOREM]. *No bilateral Bayesian-Nash incentive compatible mechanism can achieve allocative efficiency, weak budget balance and ex interim individual rationality at the same time, even if agents' utilities are quasi-linear.*

Theorem 3.1 implies that, given quasi-linear preferences of the agents, it is only possible to implement (any) two out of the three desiderata allocative efficiency, (weak) budget balance, and (interim) individual rationality regardless of Bayesian-Nash incentive compatibility is fulfilled or not.[3]

In this connection, Mas-Colell et al. [215] and Parkes et al. [260] state that budget balance and individual rationality are compulsory characteristics of a mechanism to enable sustainability over time, and thus, actually make it implementable. On the one hand, agents are not willing to voluntarily participate in a mechanism in which they expect to incur losses. On the other hand, a mechanism operator cannot continuously plough money into the mechanism.

Classic mechanism design is reflected in Vickrey-Clarke-Groves mechanisms. VCG mechanisms are direct-revelation mechanisms that are individually rational, allocatively efficient, and strategy-proof. However, VCG mechanisms are prone to cause considerable overpayments that must be subsidized by the mechanism in order to retain individual rationality. In other words, VCG mechanisms are not budget balanced, which brings about severe issues as to the mechanism's practical application, implicating a constant financial burden for the mechanism operator. Originating from the class of VCG mechanisms, classic mechanism design, or mechanism design *in the narrow sense* is closely connected to incentive compatibility.

Classic mechanism design also seeks for efficient outcomes, therefore requiring that agents reveal their private information truthfully. It is possible to construct inefficient, but incentive compatible mechanisms [235]. However, allocatively efficiency inherently requires incentive compatibility [260].

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[3] According to the revelation principle, truthfulness comes "for free" and does not have an influence on the impossibility of simultaneously achieving allocative efficiency, budget balance, and individual rationality.

Another fact speaking for incentive compatible mechanisms is, from a designer's perspective, to be found in terms of the desired result. Designing a mechanism, one is to choose the set of possible strategies and the allocation and transfer function in a way that the agents' behavior, though self-interested, is *predictable* for the mechanism operator. An incentive compatible direct-revelation mechanism $\mathcal{M}$ implements the social choice function $f(\theta) = m(\theta)$. Thus, in an incentive compatible mechanism, the outcome rule equals the preferred system-wide solution, which discernably facilitates predictability [257].

However, as Parkes et al. [260] argue, *second-best mechanism design* or *non-incentive compatible mechanism design* as a mechanism design approach in the broader sense *can* actually be useful, although truthful bidding is not an equilibrium strategy for agents and thereby, allocative efficiency is also sacrificed. Certainly, mechanism design in the narrow meaning does not allow for, or – formulated more precisely – does not require such a variation. In theory, non-incentive compatible mechanisms can be subsumed under the class of incentive compatible ones. According to the *revelation principle*, any social choice function realized (in equilibrium) with a non-incentive compatible mechanism can be transformed into an equivalent incentive compatible mechanism where any agent directly "plays" its true type as its action [131, 234, 236]. However, and this is the crux, computational assumptions of the revelation principle are not realistic. First, it assumes that agents in the non-incentive compatible mechanism are capable of computing any of their equilibrium strategies. This is an implicit worst-case assumption of mechanism design on agents' strategic abilities, which implies that agents can always compute and exploit all opportunities for manipulation present in the considered mechanism. Second, for the submission of agents' strategies and the computation of the outcome by the mechanism operator, the revelation principle postulates unlimited computational resources [205, 258].

Yet, in selected applications and from an economic standpoint, it might not be the ultimate goal to achieve a truthful revelation of the agents' types "at any cost". Sacrificing incentive compatibility in favor of other properties can be reasonable in order to obtain a "good (enough)" result. Even if incentive compatibility is not given, the agents' behavior can still be predictable in a sense that the social choice is met *in a broader sense*. On the other hand, if incentive compatibility is to be enforced, inefficient solutions might be the result – and such inefficiency can be enormous as incentive compatible and budget balanced as well as individually rational mechanism implementations give proof of (cp. e.g. [217, 25]). Yet, it is possible to achieve less inefficient allocations without insisting on truthful information revelation [260].

Generally speaking, the design of a mechanism obviously depends on the overall goal pursued featuring an inherent trade-off between design desiderata. Therefore, not every mechanism design approach ultimately longs for achieving incentive compatibility. For instance, Parkes et al. [260] seek to implement budget balance and individual rationality in a combinatorial auction setting by sacrificing incentive compatibility (and therefore allocative efficiency) to different degrees. Blau [45] proposes a VCG-based mechanism to allocate multidimensional service offers, however, counteracts the overpayments by introducing an extension that sacrifices incentive compatibility in favor of budget balance.

3.1.5 Computational Mechanism Design

The origin of *algorithmic* or *computational mechanism design* is that classic mechanism design largely ignores the complexity of solving optimization problems. Pioneered by Nisan and Ronen [244], this notion has considerably changed by bringing together mechanism design and algorithmic issues, incorporating computational feasibility.

Classic mechanism design implicitly follows two major assumptions. On the one hand, agents are able to compute and to communicate their complete preferences. On the other hand, the mechanism itself has the capacity to compute the correct outcome, taking into account the complete and relevant information within the system. One can distinguish several sources of complexity, however, with respect to quasi-linear mechanisms, the determination of the allocation rule $o(\cdot)$ and the transfer function $t(\cdot)$ is usually referred to as the weightiest criterion [245, 257]. Such complexity might clash with the practical application of mechanisms if resources for computation are limited.

Theoretical computer science yields well-established concepts to measure complexity by basically differentiating between algorithms that belong to the class P, which can be computed in polynomial time, and algorithms that are assigned to the class NP, which are subject to exponential complexity. These complexity considerations can be transferred to mechanism design as stated in the following definitions [245].

Definition 3.15 [POLYNOMIAL MECHANISM]. *A mechanism is polynomial if its outcome rule* $m\left(o(\cdot), t(\cdot)\right)$ *can be computed in polynomial time.*

Definition 3.16 [NP-COMPLETE MECHANISM]. *A mechanism is said to be NP-complete if at least one element of its outcome rule* $m(\cdot)$ *exhibits exponential complexity.*

In real-word scenarios, *computational tractability* can be a desirable property, especially if the mechanism's outcome rule needs to be determined at runtime [296].

Definition 3.17 [COMPUTATIONAL TRACTABILITY]. *A quasi-linear mechanism is computationally tractable if both* $o(\cdot)$ *and* $t(\cdot)$ *can be computed in polynomial time for all* $\omega \in \Omega$.

The tension between computational tractability and desirable game-theoretic properties can be tackled differently. On the one hand, and analogue to the approach of non-incentive-compatible mechanism design, by approximating $o(\cdot)$ and/or $t(\cdot)$, the mechanisms' tractability can often be restored at the price of breaking incentive compatibility and therefore allocative efficiency [260]. That is, computational mechanism design sacrifices *economically* efficient outcomes in order to guarantee *computational* efficiency. On the other hand, alternatives to approximation are the identification of polynomial special cases of the generally NP-complete problem, or a deflection from centralized mechanisms to a distributed computation. The latter requires a decentralized computation of a mechanism's outcome where the mechanism is no longer a distinct entity but rather spread over the agents [119]. This approach suits decentralized applications such as peer-to-peer or grid computing scenarios [91].

Computational mechanism design has been applied in a multitude of scenarios. The following list of scholars is just a rough overview of the huge body of work available. One of the most prominent applications of computational mechanism design are routing problems. Feigenbaum et al. [119], Archer et al. [13] consider cost-sharing algorithms for multicast transmission[4] consulting approximation techniques and distributed computing. Another NP-complete problem that has recently been reviewed via distributed computation and specialization to polynomial cases is interdomain routing, that is, routing of traffic between Internet domains [295, 118, 120, 345]. Moreover, grid computing scenarios offer a vast application area for distributed computing as shown, for instance, by Stösser [306], who presents a heuristic scheduling algorithm to restore computational tractability in grid settings by sacrificing incentive compatibility to a certain extent. However, not only Internet applications trigger algorithmic mechanism design endeavors. Generally, several scholars examine *approximate truthful mechanisms* for the (intractable) class of combinatorial auctions [206, 232, 204].

3.2 Cooperation & Network Design

As introduced in Section 3.1, mechanism design follows the approach of determining which rules a *non-cooperative game* needs to exhibit in order to achieve a certain system-wide preferred outcome, i.e. a *cooperative solution* [160]. While non-cooperative game theory has to deal with opportunistic agents that act according to their self-interest, cooperative game theory studies the interaction among coalitions of agents[5] and implies the possibility to exogenously enforce commitments between them. The latter requires communication between agents. Such communication can be either direct among the agents or indirect via a third party to which the agents can commit themselves. Cooperative game theory yields several solution concepts for coalition games that are concerned with the question of how to distribute a given set of "coalition payoffs" to each of the contributing agents [289].

The term "coalition" is misleading in a sense that it does not mean that each agent is agreeable and follows any kind of instruction [296]. Still, agents are selfish, however, can only reach certain goals as a team. Therefore, the basic modeling unit are groups of agents rather than individuals. Transferred to SVNs, it becomes obvious that the provisioning of a complex service requires a joint effort (cp. Section 2.2). Thus, cooperative game theory should certainly be considered as a means to include both individual and group incentives in the course of value creation [177].

Yet, cooperative game theory originally considers coalition structures, that is, assumes that each of the agents can team up with any other agent or coalition of

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[4] Multicast routing denotes an Internet packet transmission that addresses and delivers the same packet to multiple destinations [93, 121].

[5] Cooperative game theory literature speaks of "players" rather than "agents". In order to retain consistency to Section 3.1, the term *agent* will be used further on in line with scholars that highlight cooperative game theory from a computer science perspective [177, 296].

agents. However, many real-world applications make it necessary to not only focus on the identities of the agents, but also on how they are connected to each other. This gap was bridged by Myerson [233] who transferred cooperative game theory to *network games*, considering distinct linkages between agents. Since then, different lines of research have been scrutinized to analyze network games, for instance, with respect to network formation or value distribution (cp. e.g. [175, 170, 135, 173]).

This section continues with a discussion of solution concepts as put forth by cooperative game theory and network games. Section 3.2.2 will give a brief introduction to network formation. Finally, desirable properties of solution concepts in cooperative game theory and networks games are outlined in Section 3.2.3.

3.2.1 Value Distribution in Cooperation and Network Games

Solution concepts in cooperative game theory are concerned with finding ways to divide jointly created value among single agents [296]. Generally, such solution concepts can take two fundamentally different approaches considering their type. On the one hand, *set-valued* cooperative solution concepts such as the core [133] or stable sets [241] assign a set of possible payoffs to agents (cp. Section 3.2.1.2). On the other hand, *single-valued* solutions award a unique payoff to each agent.

3.2.1.1 The Representation of Cooperative Games

In order to discuss above-named solution concepts, a representation form of the game shall be introduced. Let again $I = \{1, ..., n\}$ be the set of n agents. Let $\mathcal{K}$ denote the set of coalitions of agents in I such that $\mathcal{K} = \{K \mid K \subseteq I\}$, $|\mathcal{K}| = \mathcal{P}(I)$. At bottom, cooperative game theory seeks to figure out to which extent a coalition K can reach a jointly pursued goal without the contribution of the other agents in I that are not a member of K [299]. To this end, for each coalition $K \in \mathcal{K}$, a characteristic function $\tilde{\chi}(K) \in \mathbb{R}$ can be determined which maps a coalition of agents into real numbers as initially introduced by von Neumann and Morgenstern [241], thereby describing the coalition's value. $\tilde{X}$ shall denote the set of all generally possible characteristic functions.

In this thesis, the discussion is restricted to games with transferrable utility. Transferable utility denotes the assumption of an existing medium of exchange (e.g. *money*) that can be transferred freely between the agents [149]. This assumption coincides with the transfer across agents in quasi-linear utility functions as used in non-cooperative game theory (cp. Definition 3.4). Assuming transferable utility, the characteristic function describes the characteristic function form of a game if $\tilde{\chi}(\emptyset) = 0$ and superadditivity of the characteristic function are fulfilled.

Definition 3.18 [SUPERADDITIVITY]. *A characteristic function is superadditive if the value of the set union of two disjunct subsets of I is never less than the sum of the values of these subsets. For all $K, T \subseteq I$*

$$\tilde{\chi}(K \cup T) \geq \tilde{\chi}(K) + \tilde{\chi}(T), \quad \text{if } K \cap T \neq \emptyset \tag{3.6}$$

Building on Definition 3.18, characteristic functions can be defined as follows [279]:

Definition 3.19 [CHARACTERISTIC FUNCTION]. *A characteristic function* $\tilde{\chi} : \mathcal{K} \rightarrow \mathbb{R}$ *maps any subset* $K \subseteq I$ *to a real number* $\tilde{\chi}(K)$ *which represents the worth of the coalition* K *in terms of how much value or utility the members of this coalition can divide among themselves.* $\tilde{\chi}$ *must be defined on all subsets of* I*, requiring* $\tilde{\chi}(\emptyset) = 0$ *and superadditivity.*

In the words of Shubik [298], the characteristic function expresses the *worth of joint coordinated action of the agents within a coalition*. Based on Definition 3.19, a *cooperative game* can be defined as a pair $(I, \tilde{\chi})$ [334, 296].

Definition 3.20 [COOPERATIVE GAME]. *A cooperative game, or a game in coalitional form, is a pair* $(I, \tilde{\chi})$ *in which* $I = \{1, \ldots, n\}$ *defines a finite set of agents and* $\tilde{\chi} : \mathcal{P}(I) \rightarrow \mathbb{R}$ *associates a payoff to each coalition* $K \subseteq I$.

3.2.1.2 Set-Valued Solution Concepts

In this section, the *core* and the *stable sets* as the most prominent set-valued cooperative solution concepts are briefly introduced. Generally, the concepts assume that the grand coalition, that is, the coalition including all agents in I, always creates the highest worth. For set-valued concepts, non-dominated payoff vectors $x = (x_1, ..., x_n) \in \mathbb{R}^n$ are of major importance. In more detail, a payoff vector x dominates the payoff vector x' via K (short: *x dom x′ via K*) if $x_i \geq x'_i$ for all $i \in K$ and if there is at least one $i \in K$ with $x_i > x'_i$ and $\sum_{i \in K} x_i \leq \tilde{\chi}(K)$.

The *core* $\mathcal{C}(I, \tilde{\chi})$ can be interpreted as a solution that provides stable outcomes if unrestricted coalitional interaction is assumed. In other words, the core assigns a set of payoff vectors for the grand coalition that is not dominated by any other coalition.

Definition 3.21 [CORE]. *A payoff vector x is part of the core if and only if there is no coalition K such that x′ dom x via K.*

The core can both be ambiguous if more than one or several payoff vectors fulfil Definition 3.21 and empty if every payoff vector in the game is dominated [289].

Example 3.1 [THE THREE-AGENT MAJORITY GAME]. *Consider a game with* $I = (1, 2, 3)$ *where a majority of two agents suffices to decide upon how a certain amount of money is divided among the three agents. So,* $\tilde{\chi}(K) = 1$ *if* $|K| \geq 2$ *and* $\tilde{\chi}(K) = 0$ *if* $|K| < 2$*. Obviously,* $\mathcal{C}(I, \tilde{\chi}) = \emptyset$*, since the game exhibits cyclic majorities: the vector* $x = (\frac{1}{3}, \frac{1}{3}, \frac{1}{3})$ *is, for instance, dominated by* $x' = (\frac{1}{2}, 0, \frac{1}{2})$ *for agents 1 and 3. In turn,* $x'' = (0, \frac{1}{3}, \frac{2}{3})$ *would be preferred by agents 2 and 3. To close the cycle, agent 1 and 2 could now block* x'' *by opting for* $x''' = (\frac{1}{2}, \frac{1}{2}, 0)$*, and so on.*

The *stable sets* soften the idea of the core by suggesting "reasonable" allocations of the worth held by the grand coalition [334]. There must not be any payoff vector within the stable set that is dominated by another vector within the set (internal stability). In addition, all payoff vectors outside of the stable set are to be at least dominated by one vector from within the set (external stability). This means, however, that for a solution to exist, there can still be vectors found within the stable set which are dominated by a vector outside the set.

Definition 3.22 [STABLE SETS]. *The stable set* $\mathcal{S}(I, \tilde{\chi})$ *includes payoff vectors* x *that are both (i) internally stable, that is there is no coalition* K *such that* $\exists x' \in S : x'$ *dom* x *via* K*, and (ii) externally stable, that is, for all* $x'' \notin \mathcal{S}$ *there is a coalition* K *such that* $\exists x \in \mathcal{S} :$ x *dom* x'' *via* K*.*

Example 3.2 [THE THREE-AGENT MAJORITY GAME (CONT.)]. *Again consider the game introduced in Example 3.1. In contrast to the core, the stable set is non-empty, yielding* $\mathcal{S}(I, \tilde{\chi}) = \{(\frac{1}{2}, \frac{1}{2}, 0), (0, \frac{1}{2}, \frac{1}{2}), (\frac{1}{2}, 0, \frac{1}{2})\}$*. None of these vectors is dominated by another vector within* $\mathcal{S}$*. That is, the set is internally stable. Furthermore, any vector* $x' \notin \mathcal{S}$ *must exhibit two out of the three vector components smaller than* $\frac{1}{2}$ *if one component is larger than* $\frac{1}{2}$*, due to* $\tilde{\chi}$*. In this case, two out of the three agents would always prefer one of the vectors* $x \in \mathcal{S}$ *over* x'*. Therefore,* $\mathcal{S}$ *is also externally stable.*

The stable set solution concept makes allowances to accept solution vectors that are "less instable" than others – at the price of usually having more than one, oftentimes an infinite number of feasible payoff vectors [160]. But still, the stable set can also be empty as shown by Lucas [211].

3.2.1.3 Single-Valued Solution Concepts

Set-valued solution concepts actually do capture the complexity of a cooperative game, however, they are not well determined due to their ambiguity and the possibility of them being empty. This issue is tackled by single-valued cooperative solution concepts that grant a single, unambiguous award to each agent.

The Shapley value

In analogy to set-valued solution concepts, the Shapley value [292] assumes that the set of all agents I, that is, the grand coalition is to create the highest value. However, the Shapley value dramatically differs from the above-mentioned approaches by always providing a unique solution which is based on the average marginal contribution an agent yields to each coalition $K \subseteq I$ [292, 280]. In other words, the Shapley value can be formulated as a unique function of the agents I and a given characteristic function $\tilde{\chi}$. Hence, the Shapley value can be interpreted as the average power or significance of an agent $i \in I$ relative to I.

Definition 3.23 [SHAPLEY VALUE]. *The Shapley value assigns a unique set of payoffs* $\Phi^{SV} : \mathcal{K} \times \mathrm{X} \to \mathbb{R}^n$ *to be distributed to the agents* $i \in I$*. Agent* i*'s Shapley value* $\phi^{SV}(\tilde{\chi})$ *is based on its marginal contribution to each coalition it is a member of. Referring to a single coalition* $K \subseteq I$*, the marginal contribution of an agent* $i \in I$ *is the change of value* $\tilde{\chi}(K) - \tilde{\chi}(K \setminus \{i\})$ *that occurs if* i *leaves* K*. In order to single out a random coalition* K

containing i, the marginal contribution is weighted by the probability of K to form assuming that all n! orders of agents are equally likely. Extended to all coalitions i is a member of, the Shapley value evolves as

$$\phi_i^{SV}(\tilde{\chi}) = \sum_{K \subseteq I | i \in K} \left(\frac{(|K|-1)! \cdot (n-|K|)!}{n!} \right) \cdot (\chi(K) - \chi(K \setminus \{i\})) \tag{3.7}$$

$\Phi^{SV}(I,\tilde{\chi}) = \left(\phi_i^{SV},...,\phi_n^{SV}\right)$ *is the payment vector assigned to all n agents in I.*

The term of Equation (3.7) that refers to the worth is intuitively clear: whenever an agent is pivotal to a certain coalition, it accounts for an increase in value. Therefore, its Shapley value rises, weighted by the combinatoric part of Equation (3.7), which always refers to the set I of all agents. It can be understood as the $(|K|-1)!$ different possible orders of agents that were already present when i enters the coalition and the remaining $(n-|K|)$ orders of agents that will follow. In total, referring to K, there are $(|K|-1)! \cdot (n-|K|)!$ different permutations in which the set of agents $K \setminus \{i\}$ precede and the set of agents $I \setminus K$ antecede agent i. This interpretation of the combinatorics of the Shapley value is not meant to be a literal model for coalition formation, however, it is useful to understand the idea and computation of the solution [279]. The combinatorics rather denote the average marginal contribution of agent i, singling out different orders of agents [296], that is, they "place all of the agents on the same footing" [341]. The following example adapted from Myerson [233] illustrates how the Shapley value is assembled.

Example 3.3 [COMPUTATION OF THE SHAPLEY VALUE]. *Consider a game* $I = (1,2,3)$ *with* $\tilde{\chi}(K) = 0$ *for all single-agent coalitions,* $\tilde{\chi}(\{1,3\}) = \tilde{\chi}(\{2,3\}) = 3$, *and* $\tilde{\chi}(\{1,2\}) = \tilde{\chi}(\{1,2,3\}) = 6$. $n = 3$ *agents account for 6 permutations of I to be considered. For a small set of agents, the Shapley value can be calculated intuitively without fully referring to Equation* (3.7) *as shown in Table 3.1 [160]. The table elements denote the marginal contribution* $\tilde{\chi}(K) - \tilde{\chi}(K \setminus \{i\})$ *added by the agents* $i \in \{1,2,3\}$ *if the permutation indicated in the first column is to form in exactly this sequence.* $\Phi^{SV}(I,\tilde{\chi}) = \left(\phi_1^{SV},\phi_2^{SV},\phi_3^{SV}\right)$ *results from the sum of the marginal values agent i accounts for divided by the total of permutations.*

Table 3.1: Computation of the Shapley value

Possible permutations	$i=1$	$i=2$	$i=3$
(1,2,3)	0	6	0
(1,3,2)	0	3	3
(2,1,3)	6	0	0
(2,3,1)	3	0	3
(3,1,2)	3	3	0
(3,2,1)	3	3	0
Sum	15	15	6
ϕ_i^{SV}	$\frac{15}{6} = \frac{5}{2}$	$\frac{5}{2}$	1

In addition to the solution presented in Table 3.1, ϕ_i^{SV} *is exemplarily computed for agent* $i = 1$ *according to Equation* (3.7). *Agent 1 can be member of the coalitions* $\{1\}$, $\{1,2\}$, *{1,3}, and {1,2,3}. Therefore, ϕ_1^{SV} evolves as follows.*

$$\phi_1^{SV} = \frac{0! \cdot 2!}{3!}(0-0) + \frac{1! \cdot 1!}{3!}(6-0) + \frac{1! \cdot 1!}{3!}(3-0) + \frac{2! \cdot 1!}{3!}(6-3) = \frac{5}{2}$$

Computations for agents 2 and 3 can be conducted analogously.

The Shapley value is not only a single-point valued solution, but also a *normative approach*. That is, the value is set up axiomatically with the following four axioms to be fulfilled: symmetry, efficiency, additivity, and the dummy axiom [149, 279, 289]. Symmetry denotes equal treatment of substitutive agents, efficiency refers to the distribution of the full yield of the game, additivity states that values for agents aggregate if two independent games are summed up, and finally, the dummy axiom requires that agents which do not add any worth to any coalition receive a zero payment. The axioms proposed by Shapley [292] can be interpreted as *fairness axioms* [340, 149, 74, 334, 289]. In Section 3.2.3, these axioms will be discussed in depth.

Theorem 3.2 [AXIOMATIC CHARACTERIZATION OF THE SHAPLEY VALUE]. *A unique value exists that satisfies the axioms symmetry, efficiency, additivity, and the dummy player axiom – it is the Shapley value.*

Example 3.4 [THE THREE-AGENT MAJORITY GAME (CONT.)]. *Once more, referring to Example 3.1, due to the chosen characteristic functions, the agents are fully symmetric. That is, they must be treated equally by the Shapley value. Therefore, $\phi_i^{SV} = \frac{1}{3}$, $i \in \{1,2,3\}$, can be trivially derived from the axioms that characterize Φ^{SV}.*

The solution derived in Example 3.4 is not part of the core (cp. Example 3.1). The Shapley value sacrifices the stability property of the core for its universal applicability. It always yields a fair and unique result while the core can be both empty and ambiguous [296]. As Hart [149] points out, the Shapley value is an a priori measure evaluating a game *before* it is actually played. Unlike the set-valued cooperative solution concepts defined earlier, the Shapley value does not need to provide a stable result in a sense of the core or the stable sets require it and may be interpreted as the expectation or average of the set-valued solutions [278].

Variations of the Shapley value

Ever since Shapley's seminal contribution to cooperative game theory, his value has constantly been varied on. Follow-ups to Shapley [292] that are important in respect of this thesis will be sketched very briefly in the follwing.

A useful and intuitive variation is the *weighted Shapley value* that was actually introduced by Shapley [291], and later built upon by several other scholars (cp. e.g. [253, 185, 75, 247]). The weighted Shapley value allows for *assessing* agents in contrast to generally treat them equally. Its simple but handy assumption is that symmetry as required in Theorem 3.2 is not always desirable, for instance, if the agents' sizes significantly differ, or if some agents dedicate much more effort in the coalition than others which cannot be expressed via the characteristic function. The weighted Shapley will be revisited in Section 8.2.2.

The Shapley value has also been studied in large games where negligibility of single individuals can be assumed as for example the case in competitive economics or voting scenarios. Such games are called non-atomic and were firstly connected to the Shapley value by Aumann and Shapley [17]. More recently, the Shapley value has been connected to non-cooperative game theory. Among others, Gul [141], Winter [333], Hart and Mas-Colell [151], Pérez-Castrillo and Wettstein [266] have implemented bargaining procedures that exhibit the Shapley value as non-cooperative equilibrium outcome.

Finally, two classic *fields of applications* have led to slight adaptions of the Shapley value. On the one hand, the Shapley value can be applied to simple (voting) games by restricting the characteristic function to the values *0* (denoting a "losing coalition") and *1* (denoting a "winning coalition"). This solution is known as Shapley-Shubik index [293] (and was implicitly applied in Example 3.4). It can be interpreted as an agent's probability of being a pivotal agent that makes a losing coalition a winning one and vice versa. On the other hand, if the characteristic function is interpreted as a total cost function, the Shapley value and its axioms can easily be transformed such that joint costs can be allocated in a fair manner [298]. Cost allocation via Shapley-style payments has been applied in several domains, as for example in telecommunication billing [42], airport fees [208, 209], and multicast routing [119, 230] in general (cp. also Section 4.3), or in more specialized applications such as wireless ad hoc routing [61].

Other single-valued solution concepts

Besides the Shapley value, other single-valued indices have been introduced in academia. Although focussing on simple voting games akin to the Shapley-Shubik index as introduced in the paragraph above, their fundamental ideas can also be transferred to more complex characteristic functions and are, therefore, worth being discussed. As such, the Banzhaf-Penrose index [261, 24] and the Deegan-Packel index [92] are analyzed. Just like the Shapley-Shubik index, these indices must tackle the issue of assigning value to "a priori coalitions" and their members [161].

The Banzhaf-Penrose index is clearly focused on political and voting power; the number of "swings", each of them denoting that an agent has the power to make a winning coalition a losing one when leaving it, is a central concept of the index. Other than the Shapley value, the Banzhaf-Penrose index merely considers coalitions instead of permutations [160].

Definition 3.24 [BANZHAF-PENROSE INDEX]. *The (normalized) Banzhaf-Penrose index* ϕ_i^{BP} *of an agent* $i \in I$ *sets the number of swings accounted for by* i *in proportion to the total number of swings in the game.*

$$\phi_i^{BP}(\tilde{\chi}) = \frac{\textit{Number of swings of } i \ \forall\ K \in \mathcal{K}}{\sum_{j \in I} \textit{Number of swings of } j \ \forall\ K \in \mathcal{K}} \tag{3.8}$$

The Deegan-Packel index is also closely connected to political applications, however, only accounts for minimal winning coalitions, that is, each and every agent that is a member of such a minimal winning coalition must have the power to make it a losing one when opting out. A minimal winning coalition is defined as $K^{min} = \{K | \tilde{\chi}(K) = 1 \text{ and } \tilde{\chi}(T) = 0 \; \forall \; T \subset K, \; K \in \mathcal{K}\}$.

Definition 3.25 [DEEGAN-PACKEL INDEX]. *The Deegan-Packel index ϕ_i^{DP} of an agent $i \in I$ only accounts for coalitions in which agent i and any other member are pivotal in terms of making a winning coalition worthless. Each of such a minimum winning coalition is included with the same weight.*

$$\phi_i^{DP}(\tilde{\chi}) = \frac{1}{|K^{min}|} \cdot \sum_{i \in K, K \in K^{\min}} \frac{\tilde{\chi}(K)}{|K|} \tag{3.9}$$

3.2.1.4 Adapting Cooperative Game Theory to Network Games

As introduced in Sections 3.2.1.2 and 3.2.1.3, a basic assumption in a coalition is that any agent $i \in I$ is able to cooperate with any other agent $j \in I$. In connection with the grand coalition always providing the highest worth, the act of cooperation is assumed to be totally successful [289]. This does not hold true, though, for networks where due to functional or strategic restrictions, links between agents are of prime importance. So, the value that is generated by a set of agents does not only depend on the agents' very identities themselves (i.e., the coalition structure), but also on how they are linked (i.e., the network structure) [170].

Myerson [233] was the first scholar to extend a cooperative solution concept, the Shapley value, to *games in graph function form* by additionally taking care of the information about agents' connections. This extension of the Shapley value to graphs was henceforward called Myerson value.

In this respect, Myerson [233] introduced graphs on I as unordered pairs of distinct members of I. Such a link between agents i and j shall be denoted by $i;j$. The complete graph is denoted by $g^I = \{i;j \mid i \in I, \, j \in I, \, i \neq j\}$, the set of all graphs of I can then be introduced as $\tilde{G} = \{g \mid g \subseteq g^I\}$. A single element $g \in \tilde{G}$ therefore fully describes a distinct graph structure that could be present in the game. The graph structure determines which coalitions can function and which ones are infeasible. Now, the Myerson value implies that agents are eligible for cooperation whenever they are connected via an end-to-end connection, no matter if directly or indirectly across other agents. As Slikker and van den Nouweland [299], Jackson [172] point out, this situation can be interpreted rather as a communication game than as a network game. Communication games rest on the premise that agents that are able to communicate can also cooperate.

In a three-agent setting, for instance, one should differentiate between a graph $g' = (\{1;2\}, \{2;3\})$ and g^I. In g', agents 1 and 3 can communicate, however, do not exhibit a direct link whereas all possible links are established in g^I. In real-world scenarios, such a direct relation could, for example, result in higher costs, or in benefits through direct communication. This issue is not fully reflected in communication games. Network games should, therefore, capture the difference between indirect communication and a direct cooperation relation. Such a class of network games, where the value generated directly depends on the network topology and direct linkages therein, was introduced by Jackson and Wolinsky [175]. They show that the Myerson value can be directly extended from communication games to network games.

That is, the coalition concept on the one hand and the network game structure on the other need to be melted. Given any $K \subseteq I$, let $K|_g = \{i;j \mid i;j \in g \text{ and } i \in K,\ j \in K\}$ denote coalitions restricted by the given network topology, i.e. only existing links in the network are considered. In this connection, the notion of the characteristic function needs to be altered in favor of a richer object that includes the network structure besides coalitions and communication lines. Such functions were introduced as *value functions*, incorporating costs and benefits [175, 170]. A value function evolves as $\chi : \tilde{G} \rightarrow \mathbb{R}$. Let X denote the set of all possible value functions. Based on these adaptations, network games can be introduced.

Definition 3.26 [NETWORK GAMES]. *A network game is a pair (g,χ) in which g defines the set of agents $I = \{1,\ldots,n\}$ and their their connections as specified by $g \in \tilde{G}$, as well as the values $\chi \in X$ that are associated to each coalition $K \subseteq I$ subject to g.*

Based on Definition 3.26, the Myerson value can be defined for network games.

Definition 3.27 [MYERSON VALUE (IN NETWORK GAMES)]. *The Myerson value exhibits a corresponding solution in network games as an extension to the Myerson value in communication games and the Shapley value. It assigns a unique and fair payoff vector $\Phi^{MV} : \tilde{G} \times X \rightarrow \mathbb{R}^n$ to the set of agents I, while the range of possibilities to cooperate is reduced to a given network topology g. For each agent $i \in I$ the Myerson value evolves as follows:*

$$\phi_i^{MV}(g,\chi) = \sum_{K \subseteq I | i \in K} \left(\frac{(|K|-1)! \cdot (n-|K|)!}{n!} \right) \cdot \left(\chi\left(K|_g\right) - \chi\left(K|_g \setminus \{i\}\right)\right) \tag{3.10}$$

The Shapley value is obviously a special case of the Myerson value – it is the situation in which the underlying network structure is that of a complete, nondirectional graph, i.e. $\Phi^{MV}(g^I,\chi) = \Phi^{SV}(I,\tilde{\chi})$.

Example 3.5 [COMPUTATION OF THE MYERSON VALUE]. *Consider a game similar to the one introduced in Example 3.3 with $I = (1,2,3)$, $g = (\{1;2\},\{2;3\})$, and the value functions $\chi(K|_g) = 0$ for all single-agent coalitions, $\chi(\{2,3\}|_g) = 3$, and $\chi(\{1,2\}|_g) = \chi(\{1,2,3\}|_g) = 6$. The Myerson value can be computed analogously to Example 3.3 as shown in Table 3.2.*

One sees that, compared to Example 3.3, due to the no longer existing link 1;3, both agents 1 and 3 suffer a loss in favor of agent 2.

An assumption within the Myerson value inherited from the former use of characteristic functions is superadditivity (cp. Definition 3.18). But what if a smaller cooperation of agents is able to obtain a certain goal as efficient as a larger one? The

Table 3.2: Computation of the Myerson value

Possible permutations	$i=1$	$i=2$	$i=3$
(1,2,3)	0	6	0
(1,3,2)	0	6	0
(2,1,3)	6	0	0
(2,3,1)	3	0	3
(3,1,2)	0	6	0
(3,2,1)	3	3	0
Sum	12	21	3
ϕ_i^{MV}	2	$\frac{7}{2}$	$\frac{1}{2}$

application of superadditive characteristic or value functions does not cover this issue. Jackson [170] picks up this quite intuitive application. Additionally, he criticizes the fixed nature of the Myerson value, suggesting to move from value functions χ to their monotonic covers $\hat{\chi}$. Their underlying assumption is that networks are flexible – a given set of links can thus still flexibly be altered in the formation process of a network. Additionally accounting for the fact that larger cooperations might not generate any additional value compared to smaller ones, the value created by the maximum over all possible networks which could potentially form with respect to g and subsets g' thereof is considered. Therefore, $\hat{\chi}(g) = \max_{g' \subset g} \chi(g')$ holds. It is clear that, in order to account for all different potential combinations of networks for each cooperation K, the complete network among the agents in K, denoted $g^K = \{j;l \mid j \in K,\, l \in K,\, j \neq l\}$, must be included in the value. These considerations result in the player-based flexible network (PBFN) rule.

Definition 3.28 [Player-based flexible network allocation rule]. *The player-based flexible network rule assigns a unique payoffs vector $\Phi^{PBFN} : \tilde{G} \times \mathrm{X} \longrightarrow \mathbb{R}^n$ to the set of agents I, implying that, at time of network formation, the decision on with whom to cooperate and thus, on how to set the payoff vector, is still flexible and potentially subject to change. For each agent $i \in I$, the PBFN rule is defined as follows:*

$$(3.11)\quad \phi_i^{PBFN}(g,\chi) = \sum_{K \subseteq I \mid i \in K} \left(\frac{(|K|-1)! \cdot (n-|K|)!}{n!} \right) \cdot \left(\hat{\chi}\left(g^K\right) \right) - \hat{\chi}\left(\left(g^{K \setminus \{i\}} \right) \right)$$

Besides referring to the superadditive value function, Jackson's [170] fundamental criticism of the Myerson value is its fixed nature which does not allow for the consideration of alternative networks that potentially arise by changing links within the formation process. The fact that such criticism might not always be applicable notwithstanding (cp. Section 4.2), the PBFN rule leads us to another relevant aspect of network games, namely network formation.

3.2.2 Network Formation

Network games connect different individual agents whose decisions on which links to establish influence the formation and structure of the network [171]. Literature suggests a general sub-division into social and economic networks [135, 173]. Networks in the social environment include, inter alia, different kinds of relationships among individuals, such as the oftentimes referred to relation of social networks to job opportunities [63, 64] or to scientific publications [136]. Network considerations in economics have produced a huge body of work, too, be it in modeling trading or exchange relationships [314, 198] or in the sharing of risk in common projects according to given relationships [52].

In network games, there is generally some function $\phi' : \tilde{G} \times X \to \mathbb{R}^n$, howsoever calculated, which expresses the agents' individual payoffs based on the relationships described by network g and the value function χ. Therefore, the payoff granted to each agent $i \in I$ is (at least partially) dependent on the links that i and other agents have established. With respect to an agent's own possibilities to form or sever links, agents are supposed to act based on their self-interest analogue to a fundamental assumption in non-cooperative game theory subject to the awareness that teaming up with other agents may be necessary to create value. Modeling the choice if or if not to maintain links, agents form or sever relationships according to the utility that is connected with such an action. Jackson and Wolinsky [175] introduced the notion of stable pairwise links. A network is pairwise stable, if *(i)* establishing a missing link between two agents would lead to decreased utility of at least one agent and *(ii)* the deletion of an existing link would at least hurt one of the two included agents.

Definition 3.29 [PAIRWISE STABLE NETWORK]. *A network is pairwise stable if existing links cannot be deleted and missing links cannot be established without at least hurting one of the concerned agent.*

$$\forall\, i;j \notin g : \phi'_i(g \cup \{i;j\},\chi) > \phi'_i(g,\chi) \Rightarrow \phi'_j(g,\chi) > \phi'_j(g \cup \{i;j\},\chi) \tag{3.12}$$

and

$$\forall\, i;j \in g : \phi'_i(g,\chi) \geq \phi'_i(g \setminus \{i;j\},\chi) \Rightarrow \phi'_j(g,\chi) \geq \phi'_j(g \setminus \{i;j\},\chi) \tag{3.13}$$

However, the notion of a pairwise stable network is only fully applicable and substantial if approval to form or sever a links is required from both agents i and j. Considering link formation, this is intuitively the case in several social and economic contexts such as friendship ties, for instance, in web-based social networks such as Facebook.[6] With respect to trading links between buyers and sellers, both link formation and deletion can be two-sided [135].

Other fields of application require the consideration of one-sided link formation or deletion [21, 104]. This is mostly the case if relationships are directed, such as,

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[6] A friendship relation between two persons in social networks such as Facebook (`http://www.facebook.com`) must be proposed by one person and then confirmed by the other.

for instance, when establishing links across Web pages, or sending christmas gifts to business partners [135]. Economic applications of unilateral link formation do also exist as will be outlined in Section 6.3. In addition, severing links is oftentimes possible in unilateral fashion in both directed and non-directed networks unless prevented by contracts or codes of conduct. Again, consider Facebook as an example: the deletion of a friendship tie does not need to be confirmed by the counterpart. A single-sided version of Definition 3.29 will be discussed in the subsequent section.

3.2.3 Network Design Objectives

When designing a payment scheme in networks that include a potential plurality of value-creating agents, as present in service value networks, the rules of the "game" need to align with the peculiarities of the environment to be captured.

The nature of such objectives is quite divergent. On the one hand, properties from cooperative game theory can be adapted to network design. Oftentimes used in axiomatic approaches, these can be phrased in concise, granular desiderata, thus coinciding with desiderata in the narrow sense as formulated in classic mechanism design (cp. Section 3.1.3). On the other hand, more generic target settings come into play which cannot be expressed as fine-grained as a desideratum.

3.2.3.1 Properties from Cooperative Game Theory Adapted to Networks

Transferring coalition setups to network settings with agents teaming up into cooperations[7], one of the most important characteristics of a value distribution logic should be *fairness*. If more than one agent contributes to the overall goal or activity to be delivered, and at the same time, sophisticated contracts or bargaining procedures are unrealistic, value allocation is required to be perceived as "fair" by the participants in order to stimulate and support vigorous business activity. This is especially the case if jointly created surplus cannot be precisely accredited to the contributors.

Cooperative game theory yields a multitude of axioms to transcribe *fairness*. Their origin is to be found in Shapley [292], using a set of properties, or axioms, to account for a fair allocation rule that distributes generated value among participating agents (cp. also Section 3.2.1.3 and Definition 3.23). In the following, the fairness properties proposed by Shapley [292] will be discussed. To this end, recall the basic notation introduced in Section 3.2.1: consider a set of n agents $I = \{1, ..., n\}$ that is acting in some network game (I, χ) in which $\chi \in X$ is defined as a value function. Let $\mathcal{K}$ denote the set of cooperations of agents in I such that $\mathcal{K} = \{K \mid K \subseteq I\}$. Network structures are denoted by $g \in \tilde{G}$. Further, $\phi'_i(g, \chi)$ denotes some payoff that is assigned to agent i subject to the network structure.

The first fairness axiom requires that the full value generated by the network is to be distributed to the participating agents such that "no money is left on the table" [299].

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[7] It is referred to *cooperations* rather than to *coalitions* to account for the underlying network structure that determines which agents can cooperate.

Definition 3.30 [EFFICIENCY]. *Efficiency denotes that the maximum output of the game is fully allocated among the agents. Therefore, pareto optimality is always guaranteed.*

$$\sum_{i \in I} \phi'_i(g, \chi) = \max_{K \in \mathcal{K}} \chi(K|_g) \tag{3.14}$$

Pareto optimality is a necessary property, however, it is not sufficient. The full yield of the game can be distributed arbitrarily disproportional. Fairness also requires symmetry: the payment scheme should treat agents equally that contribute the same to each cooperation within the network. Symmetry can also be interpreted as anonymity, stating that the names or identities of the agents can be changed without altering their payoffs. The latter is only sensitive to how the value function rates the agents' presence in a cooperation, that is, to the agent's structural role [279, 341].

Definition 3.31 [SYMMETRY]. *Two agents i and j are symmetric regarding the game (I, χ) if they yield exactly the same marginal contribution to each cooperation such that $\chi(K|_g \cup \{i\}) = \chi(K|_g \cup \{j\})$ for all $K \subseteq I \setminus \{i, j\}$. Such symmetric agents must receive identical payoffs:*

$$\phi'_i(g, \chi) = \phi'_j(g, \chi) \tag{3.15}$$

The third property is expressed via the additivity axiom which requires that the solution shall be an additive operator on the space of all games X. This property states that payoffs to agents shall be the same whether two situations that consider the same set I and the same cooperation structure g – however, subject to different value functions – are evaluated jointly or separately [299, 334].

Definition 3.32 [ADDITIVITY]. *Given any two games (I, χ) and (I, χ'), the solution to the sum $(\chi + \chi')$ of the games must equal the sum of the two solutions to the single games χ and χ'. For all $i \in I$*

$$\phi'_i(g, \chi + \chi') = \phi'_i(g, \chi) + \phi'_i(g, \chi') \tag{3.16}$$

where the summed up game $(\chi + \chi')$ is defined by $(\chi + \chi')(K|_g) = \chi(K) + \chi'(K|_g)$ for all $K \in \mathcal{K}$.

The last property to describe fair solutions is the dummy axiom. The dummy (or null) property sets that agents which add no value to every cooperation must not be remunerated.

Definition 3.33 [DUMMY]. *If an agent $i \in I$ is a dummy, i.e. its marginal contribution to every cooperation is null, it is assigned a zero payoff.*

$$\phi'_i(g, \chi) = 0 \text{ if } \chi(K|_g \cup \{i\}) - \chi(K|_g) = 0 \quad \forall K \in \mathcal{K} \tag{3.17}$$

Fairness is the outcome of all these axioms taken together [292, 289]. Over the years, the fairness axiomatization proposed by Shapley [292] has been subject to variations to highlight different aspects of fairly distributed payoffs. A variety of different axiomatizations has been proposed by different scholars (cp. e.g. [340, 341, 74, 150]). As these axiomatizations are equivalent to the one presented in this section, further details are cautiously put aside in this thesis.[8]

Besides fairness, other related properties can be considered. Cooperational monotonicity[9] is akin to fair division of value as it requires that, if the underlying structure of a game changes (which can be expressed via a change in the value function), payoffs must also change in the same manner [298, 340]. This is a vital property in order to retain competitive forces in the network: efforts of agents to increase their efficiency in whatever way may not be punished by decreasing payoffs.

Definition 3.34 [Cooperational monotonicity]. *Cooperational monotonicity states that if a particular cooperation $T \in \mathcal{K}$ increases its value while the value of all other cooperations $K \in \mathcal{K} \setminus T$ remains fixed, none of the agents in T ia worse off than before. This coherency can be re-formulated such that*

$$\begin{aligned} \forall\, K = \{K|i \in K\} : \chi(K|_g) \geq \chi'(K|_g) \wedge \forall\, K = \{K|i \notin K\} : \chi(K|_g) = \chi'(K|_g) \\ \Rightarrow \phi'_i(g,\chi) \geq \phi'_i(g,\chi') \end{aligned} \tag{3.18}$$

The last property listed in this section is closely connected to the existence of set-valued solutions in cooperative game theory (cp. Section 3.2.1.2). If a solution yields a multitude of payoff possibilities for a single agent, value cannot be reasonably and fairly distributed since the solution is ambiguous.

Definition 3.35 [Uniqueness]. *The solution concept is unique for any game (I,χ) if*

$$\forall\, i \in I : \phi'_i(g,\chi) = x,\ x \in \mathbb{R}^1 \tag{3.19}$$

3.2.3.2 Properties from Network Games

Properties in network games can be both akin to fine-grained desiderata of network games presented in the previous section and formulated more globally. Aberrant from the general approach in this chapter, the target settings are not exclusively stated neutrally but are partially elucidated by drawing on the service value network context.

Link formation in the network

As introduced in Section 3.2.2, the formation of networks has been extensively discussed in economic theory. A standard objective pursued is *stability*. Depending on

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[8] The interested reader may want to refer to the original references or to Winter [334] for a survey.

[9] In Young [340], this property is named *coalitional monotonicity*. This term is mapped to the underlying network structure in network games.

the links' types and formation assumption, *pairwise stability* as introduced in Definition 3.29 is a reasonable desideratum. With respect to networks with directed relationships, *individual stability* is a more substantial than considering both linked agents. Based on an individual agent $i \in I$ who is in charge of forming or severing, for instance, outgoing links, individual stability considers the set of any possible networks $D_i(g) = \{g' | g \setminus \{i;j\} \forall\, i \neq j,\, j \in I\} \cup \{g' | g \cup \{i;k\} \forall\, i \neq k,\, k \in I\}$ the agent can reach from a given network $g \in \tilde{G}$ by unilaterally choosing a linkage strategy [104].

Definition 3.36 [INDIVIDUAL STABILITY]. *A network g is said to be individually stable if any agent $i \in I$ cannot improve its payoff $\phi_i'(\cdot)$ by forming additional or severing existent links that are at i's command:*

$$\phi_i'(g,\chi) \geq \phi_i'(g',\chi) \forall g' \in D_i(g), i \in I \tag{3.20}$$

Besides individual stability, which does not make any statements on the *degree of interconnectedness*, other target settings with respect to link formation come into consideration. If links are interpreted as *interoperability*, or *integration* relationships, respectively, such as in the SVN environment (cp. Section 2.2.3), an as high as possible number of connections in the network can be a desirable goal. Links in SVNs denote the linkage of complementary services. In this connection, aiming at a fully intermeshed network that features all feasible links *can* be a design goal. If reaching a complete network is unrealistic, a target setting that formulates the number of integration relationships in relative terms is an alternative to above-mentioned measures. Such a relatively verbalized objective requires a comparison to benchmarks.

Network growth and incentives to join

Before discussing the means to evaluate network growth, one needs to identify the type of network that shall be analyzed. Service value networks belong to the class of two-sided markets. Two-sidedness implies that agents as introduced in this chapter are subdivided into two classes – service customers and service providers. In order to fully tap the potential of the market and establish a successful business, both buyers and sellers need to be brought "on board" [274]. Both sides of the market positively value the number of participants on the other market side. Service consumers benefit from a larger number of service providers leading to variety and competitive prices. However, sellers are only willing to register if they expect to face many buyers in the market [62]. It is obvious that the key challenge is to find a way to exploit the dependency of a network's value and the number of participants connected to it [290].

However, almost any strategic advice assumes that a captive installed base exists on at least one side of the market. If a new market is established, its operator has to decide on which side of the market demand should be stimulated first, or if there is a strategy to be adopted that is able to attract both sides of the market simultaneously. Therefore, when designing a payoff rule for a network game, especially in its launch phase, effective incentives for network participants to join and thereby boosting network growth is a major challenge.

The desired size of a network and its growth can hardly be formulated in terms of a desideratum. Incentives to join the network are rather generated through a complex system of different parameters when designing a network payoff rule. Moreover, network growth is barely measurable in absolute terms. Thus, this target setting is likely to be stated in relative terms benchmarked to scenarios that use different incentive schemes.

3.3 Summary

In Chapter 3, both economic foundations of mechanism design and cooperative game theory were outlined. From the latter, approaches to strategic network formation, known as network games, have emerged [175]. This body of work merges ideas inheriting cooperative solution concepts with explicit network structures, subject to strategic behavior of agents within the network. Abstracting to a higher level, such considerations suggest to also amalgamate design objectives from classic mechanism design and network games when designing coordination rules for co-opetitive environments such as service value networks.

Technically, mechanism design and normative solution concepts in cooperative game theory exhibit the same procedural method. On the one hand, mechanism design is also referred to as inverse game theory [296]. Unlike most of the approaches from non-cooperative game theory, mechanism design sets a certain outcome of a game as its desired goal and subsequentially evaluates how to design rules such that non-cooperative agents realize this outcome as a result of their self-interested acting. This modus operandi is akin to the axiomatic approach taken by normative concepts in cooperative game theory. In normative approaches, axioms prescribing the objectives of the solution are set up and logical implications are derived [289]. In total, although stemming from the very counterparts of game theory, mechanism design and normative solution concepts from cooperative game theory are unified by their goal-driven character.

Picking up the insights from Section 2.2, environments that foster joint value creation as an outcome of specialization and modularization exhibit both competitive and cooperative features. Such application scenarios particularly suggest above-sketched fusion of concepts from non-cooperative and cooperative game theory. The co-opetition mechanism as introduced in Chapters 4 and 5 is an effort to take care of this hybrid environment and to coordinate participants that are related both cooperatively and competitively.

Part II

Rewarding Contributions to Service Value Networks

Chapter 4

Incentive Engineering in Service Value Networks

This chapter will merge the economic foundations presented in Chapter 3 with the newly arising business governance structure of service value networks as discussed in Chapter 2. In such environments, value creation is coordinated by a platform operator for the most part, as conceivable in today's leading service platforms which can be considered as SVN forerunners. Among others, Salesforce.com, Xignite, and StrikeIron operate marketplaces in order to offer composite Web services. Moreover, companies like Etelos.com with its SaaS Marketplace Platform[1], which offers to other companies frameworks to run Web service marketplaces around their core services, push into the market. A very similar concept is successfully marketed by the Chinese PaaS provider Alisoft.com[2]. These market dynamics indicate that competition between different service platforms and Web service marketplaces is already in place and will further rise as the SVN concept moves to mainstream. Companies that consider to launch an SVNs have to demonstrate competitive and innovative business models – a high-potential strategy must include an effective lever to sustainably attract market participants to the platform. In this connection, an attractive service portfolio in terms of variety and quality should be a result of the incentives given by the market.

The central research goal of this thesis is to identify and introduce such a novel incentive scheme that is custom-made for service value networks. Designing it, desired properties to be fulfilled have to be carefully evaluated, traded off, and finally defined. This thesis' approach is to consult mechanism design in a broader sense to implement a preferred system-wide solution to a decentralized optimization problem. However, individuals at the seller side of the network cannot merely draw on selfish behavior since their "fate" in terms of successful service delivery is directly connected to other vendors [166]: service providers have to effectually indicate their willingness to cooperate with distinct other service providers in a complex service offering as a very foundation and requirement for value creation. Therefore, when defining the social choice function of the mechanism, objectives from classic mechanism design, cooperative game theory, and network design come into consideration.

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[1] `http://www3.etelos.com/etelos/platform/`

[2] `http://www.alisoft.com/`

In fact, as will be outlined in Section 4.1, the implementation of network-related objectives is the center of the presented *co-opetition mechanism*, as it is henceforth referred to it.

The essence of the co-opetition mechanism can be found in the *power ratio (PR)*. Recall that an SVN is formed upon specific customer request – any complex service instance in the SVN is thus potentially able to create value. Even if non-allocated, each and every service enriches the platform's variety and makes a contribution to the overall competitive situation and the long valley's power of combinatorics. The novel approach inherited by the power ratio is to compensate vendors also for their *readiness* to deliver. In other words, the power ratio shall not only reward service providers which are actually allocated in a complex service rendered at a time, but also pay out sellers that are on standby, i.e. partners which are able to fulfill a customer request and thereby support the network's variety without actually contributing to the complex service executed. The latter shall thereby be also remunerated for their efforts to design or adapt their services according to the requirements imposed by the SVN operator. The basic idea and novelty of the power ratio as well as the reasons for its application are laid out in Section 4.2. Finally, in Section 4.3, the co-opetition mechanism is differentiated from closely related literature, thereby emphasizing the contribution of this work.

4.1 Environmental Analysis for Service Value Networks

This work will tackle the challenges brought up by service value networks from an *operator's point of view*. The role of the operator of the SVN coincides with the role of the mechanism operator. That is, the mechanism is centralized, implying that it is an individual and self-contained unit in the overall system. For the participating agents, the mechanism is understood as an impartial component that enables communication and directly connects the agents in the network [305]. Such centrality in terms of operation can be assumed in service value networks: service offerings are provided by decentralized vendors, however, are composed and offered to the service customer via a central entity, as today's SVN forerunners substantiate (cp. Section 2.2.4).

As discussed in Section 3.2.3.2, the platform operator needs to attract service providers and service customers with both sides valuing participants on the other market side [62, 274]. With either market side being initially vacant, we face a typical chicken-egg-problem. If a new platform is to be launched, its operator needs to decide which side of the market should be stimulated first in order to subsequently capture the other market side as well. In this thesis, an approach akin to the divide-and-conquer approach in two-sided market theory is pursued [62]: participation at one side of the market is cross-subsidized and recovered by the other market side [115]. Additional payments are made to the service provider-side by the service customer who is assumed to be willing to pay a premium for the value proposition that is quintessential to SVNs, first and foremost, the radical cutback of lock-in risks. Such lock-ins that prevent customers from using services of competing companies cannot be held up anymore on a functional level. In SVNs, customers can easily switch from one service to a substitutive one due to the services' modularity and compatibility with switching costs decreasing to a minimum [116]. In the traditional software business that features large upfront investments in form of long-term licences and maintenance agreements, the customer is particularly prone to strong financial ties that hinder her to change software vendors – although others might offer more suitable or cheaper solutions [103]. This "classic" lock-in situation has already diminished by the move towards software-as-a-service. SVNs take this characteristic to extremes by *additionally allowing for single switches even within the complex service*. This is certainly a severe source of risk for service providers as they become replaceable, which increases the competitive pressure, in turn having a positive effect on the service providers' efficiencies in terms of costs and quality.

Service customers are likely to be willing to pay a premium for such reduction of lock-in risk and variety of options to choose from, which makes them more independent of unsteady quality of service or price variations. In the course of increasing replaceability of service providers, for the service customer, the origin of the component services comes second [100]: service providers' identities take a back seat while the services themselves are of prime importance. This statement is true as long as functionality and quality meet the customer's requirements, subject to a trustworthy overall concept. Recent studies verify this trend by finding that at least small enterprises increasingly tend to disregard providers' identities as long as a certain quality is plausibly guaranteed [102].

Thus, this thesis' approach is to set up incentives for the service provider side, which are then assumed to generate positive feedback upon the service customers and vice versa.

4.1.1 Networked Mechanism Design

As argued earlier, operators of SVNs do not only need to design innovative and elaborate business models but also have to hold effective incentive schemes ready. The latter is crucial in order to pull participants onto the offered platform and to make sure that they remain there. This is where mechanism design comes into play. Its main question is not what will happen in a specific interaction of various agents, but rather how to tackle the challenge of having a desired outcome in mind and to comprehend which strategic interaction and which setting could lead to a course of action that implements this very outcome [296]. An SVN operator has to deliberately cogitate about this issue when starting a new platform. Besides making a profit in the medium term, which short-term goals should be pursued to get a business up and running? So, it is all about *incentive engineering* – and this is exactly what mechanism design can be ideally applied for. However, mechanism design in its classic form does not always hit the target. This issue has been illustrated in approaches that waive the classic mechanism design requirement of incentive compatibility, and therefore, also sacrifice allocative efficiency, such as second-best mechanism design [260] and computational mechanism design [245] (cp. Sections 3.1.4 and 3.1.5).

Building thereupon, the *networked mechanism design (NMD) perspective* is introduced in this thesis. Unlike second-best mechanism design or non-incentive compatible mechanism design, not only sacrifice classically applied desiderata are sacrificed in order to approximate other objectives. Networked mechanism design is rather geared to sacrifice certain classic properties in order to achieve alternative objectives that are closely connected to the networked scenario. NMD incorporates the requirements that are imposed by newly arising networked scenarios where a set of agents must co-operate to create value, however, competes when it comes to distributing revenues that arise from the joint value creation. This area of conflict is inherent to problem sets in networked scenarios such as incentive engineering in SVNs. Yet, the herein included desired properties are disregarded in classic mechanism design.

Two concrete consequences applying networked mechanism design must be paid attention to. On the one hand, network design properties are potentially likely to differ from traditional desiderata. While the latter are traditionally stated in a highly granular format, the social choice in networked mechanism design might pursue *target settings* rather than fine-grained desiderata. Such target settings cannot be formulated in an absolute manner but must be stated in relative terms. In this case, a comparison to a suitable benchmark is required. On the other hand, akin to second-best mechanism design and computational mechanism design, classic mechanism design desiderata are likely to fall victim to the must-have goals pursued. Other than in second-best mechanism design, the latter must not necessarily be a consequence of impossibility theorems that constrain the design space of mechanisms, but can also be owed to other, prioritized objectives of the desired social choice (cp. Section 5.2.1).

4.1.2 Social Choice of the Co-Opetition Mechanism

Following networked mechanism design, in order to capture an SVN's co-opetitive nature, both aspects from classic mechanism design and from network design are involved when defining a system-wide preferred goal. In the following, the requirements of a mechanism that is capable of supporting an SVN's potential to economically exploit the *long valley* of complex services is set out and substantiated. As most of the objectives were discussed in detail in Sections 3.1.3 and 3.2.3, their explanation is kept brief while putting the emphasis upon the objectives' qualification for the SVN context.

Taking the platform operator's view in the *launch phase of an SVN*, fueling initial business must be the main goal. The key objective is to define incentives that activate network effects and open out into positive feedback loops that give rise to self-reinforcing success: the more service providers join the SVNs with their service offerings, the higher the value of the complex service portfolio experienced by the customer. At the same time, this makes the network more attractive for new vendors, which in turn draw in more customers [15, 290, 188]. Therefore, profit maximization of the platform operator in an optimal auction-like approach is not a primary aim at this stage of business and is therefore not pursued in this work. It is rather important to support and activate a healthy and preferably rapid network development.

Two central and crucial objectives shape the proposed mechanism that stand above profit making in the short run. First, it is the mechanism's ability to set effective incentives for participants to join, thereby increasing the network's overall size. Second, such growth shall be sustainable. Therefore service providers should be compensated for steadily offering their services in the network after their entry to the SVN.

Waiving profit maximization does not mean that the platform operator needs to exhibit altruistic features. Quite the contrary – once a critical mass is reached, a different mechanism including, for instance, participation fees or variable commissions can be implemented. The faster such a critical mass is achieved, the earlier a platform is likely to become profitable [188]. Hence, the first two objectives of the co-opetition mechanism can be stated as follows:

Requirement 4.1 [NETWORK GROWTH]. *The co-opetition mechanism shall be able to incentivize service providers to join the network. That is, it shall be able to foster network growth (cp. Section 3.2.3.2).*

Requirement 4.2 [READINESS TO DELIVER]. *The co-opetition mechanism shall be able to incentivize service providers to constantly and continuously keep ready their services in the network. That is, service providers shall be rewarded for steadily being able to offer a service.*

Thus, Requirement 4.1 shall attract previously non-allocated service providers while Requirement 4.2 is targeted on service providers that are already a part of the SVN. Yet, the two requirements are interdependent in a way that the incentives for being ready can and most probably will influence a service provider's decision to actually join the network.

If such readiness shall be compensated for by granting monetary means to more than the allocated service providers in the SVN, the distribution logic must be fair. On the one hand, it is obvious that service providers that make greater contributions to the aggregate system's overall value need to receive a greater share of it. On the other hand, a distribution logic needs to be conceived as generally evenhanded by participating providers in order to gain acceptance.

Requirement 4.3 [FAIRNESS]. *The co-opetition mechanism shall distribute payoffs among service providers as demanded by Requirement 4.2 in a fair manner. Fairness assembles from the four specific properties efficiency, symmetry, additivity, and the dummy property (cp. Definitions 3.30 – 3.33).*

Further, uniqueness of the payoff rule is unwaivable, since every provider's share in the overall amount of money to be distributed must be distinct. Otherwise, the mechanism shows features of a lottery and is deemed to fail.

Requirement 4.4 [UNIQUENESS]. *The co-opetition mechanism shall distribute payoffs in a unique manner (cp. Definition 3.35).*

Requirement 4.5 states a desirable incentive property: providers are incentivized to make their services more efficient. Vice versa, cooperational monotonicity does still allow for the following situation: an increase of one service's efficiency does not decrease other cooperation's value functions, however, it can very well decrease the other services' payoffs. That way, competitive pressure is retained and reinforced.

Requirement 4.5 [COOPERATIONAL MONOTONICITY]. *The co-opetition mechanism shall be cooperationally monotonic. That is, a service provider within the network that is able to increase its individual worth for the network must not be worse off in terms of its payoff than before (cp. Definition 3.34).*

Interconnectedness or integration of services is another highly important issue in SVNs since complementarity can only be fully leveraged if the very interplay of services is guaranteed in the first place [106]. Link formation is discussed in depth in Sections 3.2.2 and 3.2.3.2. Transferred to service value networks, links, i.e. edges e_{ij} in the network, indicate that services v_i and v_j are composable. Whether two services are connected basically depends on two factors, namely functional and strategic criteria. As functional interoperability is generally given due to the requirements imposed by the platform, decisions on being linked or not mainly depend on strategic considerations. In SVNs, links can be formed by individual decision since a service provider cannot influence which other vendors use the output of its service. Thus, we are located in the sub-field of one-sided link formation with individual stability (cp. Definition 3.36) as a possible design goal. Apart from the network being stable, a high degree of interconnectedness is desirable for several reasons. As mentioned above, interconnectedness is the key enabler for complementarity: without suitable incentives for link formation, cooperation between service providers that offer complementary functionality is impaired. Secondly, customers are expected to prefer purchasing services in networks yielding alternative, substitute offerings such that other providers can dynamically pitch in if an allocated service goes out of business. This is particularly true for critical business applications. Furthermore, such a configuration dramatically decreases customer lock-in. Finally, promoting alternative paths through the network leads to a more balanced network without single providers having monopolistic positions. In such balanced networks, the platform operator is no longer dependent on powerful service providers which could impose pressure by bulling the market or by threatening the network with termination of membership. Therefore, a steadily reached high degree of interconnectedness is a desirable goal in SVNs.

Requirement 4.6 [HIGH DEGREE OF INTERCONNECTEDNESS]. *The co-opetition mechanism shall account for a high degree of interconnectedness among services.*

The network design related objectives notwithstanding, we must foremost keep focus that we are working within the boundaries of mechanism design. Following Parkes [257], the co-opetition mechanism is required to be budget balanced and individually rational. Budget balance ensures financial viability in the mid-term since the platform operator does not need to subsidize transactions made via the platform.[3]

Requirement 4.7 [BUDGET BALANCE]. *The co-opetition mechanism shall be budget balanced. Payments made to participants need to be fully refunded by payments made by other participants. In order to comply with fairness (cp. Definition 3.30 and Requirement 4.3), surplus funds must be entirely redistributed (cp. Definition 3.10).*

Individual rationality is vital since participants are not willing to voluntarily participate if they are at risk of incurring losses.

Requirement 4.8 [INDIVIDUAL RATIONALITY]. *The co-opetition mechanism shall be individually rational. Participants should not be worse off by participating than by waiving participation (cp. Definition 3.11).*

Finally, the co-opetition mechanism needs to be capable of handling service composition and QoS characteristics as introduced in Section 2.2. For the former, it is not enough to process bundles without considering the elements' sequence [2, 287, 20]. As shown in Section 2.2.1, in SVNs it is essential to also account for the services' order in the complex service, since value is only generated in the right sequence of components. Further, the multiattributive nature of services needs to be considered because non-price attributes play a crucial role when allocating a complex service (cp. Section 5.1.1).

Requirement 4.9 [SEQUENCE-SENSITIVE SERVICE COMPOSITION]. *The co-opetition mechanism needs to be capable of handling well-defined sequences of service components in order to allocate a feasible complex service.*

Requirement 4.10 [QUALITY OF SERVICE SENSITIVITY]. *The co-opetition mechanism needs to account for multiple attributes that define the complex service's QoS characteristics.*

To summarize, the requirements made on the co-opetition mechanism can be sub-divided into three classes as illustrated in Figure 4.1. First, desiderata and target settings from network design (Requirements 4.1 to 4.6) are required, some of them inspired by cooperative game theory. Second, desiderata from mechanism design come into play (Requirements 4.7 and 4.8) while other classic mechanism design properties such as allocative efficiency and incentive compatibility are sacrificed. This does, however, not mean that they can generally be neglected as will be shown in Part III of this thesis. Third, Requirements 4.9 and 4.10 define the class of applicability requirements.

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[3] Certainly, costs for erecting and operating the platform including auxiliary services still need to be borne. Such expenditures as well as the design of a pricing model including membership and transaction fees are not considered in this thesis.

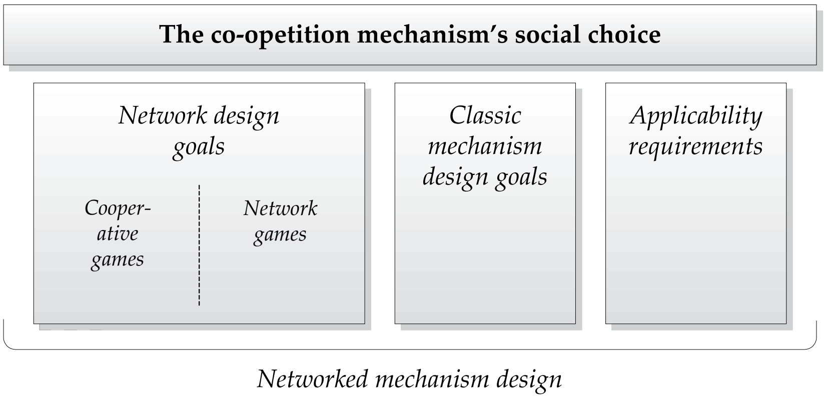

Figure 4.1: Social choice of the co-opetition mechanism

4.2 Introducing the Power Ratio

As outlined in the introduction to this chapter, the co-opetition mechanism's central concept is to compensate not only the set of allocated service providers, but all available service providers that are able to fulfill a specific customer request. This logic shall reflect the network design objectives erected in Requirements 4.1 to 4.6. In the remainder of this thesis, the SVN-specific notation introduced in Section 2.2.3 will be consulted. Let further Δ denote a monetary surplus that is tendered in order to fund the above-stated compensation. δ_j indicates v_j's share in Δ. In general, such a payment t_j granted to each service $v_j \in V$ can be assembled as follows:

$$t_j := \begin{cases} p_{ij} + \delta_j, & \text{if } v_j \text{ is allocated via its link } e_{ij} \\ \delta_j, & \text{if } v_j \text{ is not allocated} \end{cases} \tag{4.1}$$

Consequently, the payoff T_h for a service provider n_h that owns several service offers v_j in the SVN assembles as follows:

$$T_h := \begin{cases} \sum\limits_{\substack{e_{ij} | e_{ij} \text{ allocated,} \\ v_j \in \sigma(n_h)}} p_{ij} + \sum\limits_{v_j | v_j \in \sigma(n_h)} \delta_j, & \text{if at least one } e_{ij} \text{ with } v_j \in \sigma(n_h) \text{ is allocated} \\ \sum\limits_{v_j | v_j \in \sigma(n_h)} \delta_j & \text{if none of } n_h\text{'s services are allocated} \end{cases} \tag{4.2}$$

Example 4.1 [Payoff Distribution]. *Consider a complex service F_1 that creates a value of x, howsoever calculated. Now assume that there is a different path F_2 exhibiting a value of $x - \varepsilon$. If F_1 was to go out of business, choosing F_2 would only yield a loss of ε. Therefore, the full payoff should not be ascribed to F_1, but also consider any other complex service F_l that has a positive value.*

Example 4.1 shows that the idea of the payment introduced in Equations 4.1 and 4.2 directly takes on Requirement 4.2. By not only rewarding service owners whose services are actually allocated in a specific service composition, but also potential creators of value, service providers that keep ready their resources are granted a percentage of the overall surplus distributed. However, Requirement 4.1 is also addressed, albeit not as directly as readiness, which can be explained by a reduction of risk in the highly agile SVN context. Service providers are likely to face initial and specific investment costs when designing or adapting services that meet the requirements imposed by the SVN as, for instance, is evident in salesforce.com's AppExchange or in TEXO (cp. Section 2.2.4). Such investments have to be made prior to any transaction, enhancing or facilitating the value of the trade within the platform, but being of considerable less value outside of the platform [109, 129]. These specific investments might prompt sellers not to join an SVN since future revenues and transactions are too uncertain compared to the initial investments [276]. Knowing that there will be a recurring payment even if one's service is not regularly allocated might lower the entry barrier for service providers, somewhat providing security through reconciliation of interests in the *initial phase* of the SVN. In order to boost network growth and foster increasing returns, it is inevitable to attract a critical mass of participants. Speaking of service providers, these participants do not necessarily have to be the most competitive ones - as long as the mass of vendors attracted make sure that a sufficiently large number of customers enter the platform. If the SVN is successful in attracting a "good" share of potential customers, previously non-attracted providers might also feel impelled to join the SVN [290].

By rewarding all potential creators of value, not only the ones that are actually allocated, service providers are not only likely to join the SVN, but also remain there as their readiness to deliver is explicitly rewarded (cp. Requirement 4.2).

These payoffs as sketched in Equation (4.1) shall be realized by the *power ratio*. The power ratio will be based upon Shapley-style calculus (cp. Definition 3.23). Transfering the logic of the Shapley value to SVNs, the PR can be interpreted as the average power or significance of a service $v_j \in V$ relative to G (cp. Section 3.2.1.3, in particular Definition 3.23). Shifting the traditional notion of purely allocation-based payoffs towards a redistribution among all vendors that are able to provide value for the network is a radical step and necessitates fair distribution (cp. Requirement 4.3). Such fairness is an inherent property of the Shapley value. Yet, the market would be threatened by adverse selection [4] if the power ratio-based payments were not aligned with the competitive environment (cp., in particular, Requirement 4.5). By valuing marginal contributions, the Shapley value exhibits appropriate characteristics. Transferred to the objective of SVNs, namely providing customers with complex service offerings, the PR needs to quantify a service provider's marginal contribution at the complex service level.

Besides above-mentioned properties, the Shapley value brings about another requirement surveyed in Section 4.1: its solution is *unique* (cp. Requirements 4.4). By this requirement, set-valued solution concepts as introduced in Section 3.2.1.2 are directly ruled out. Other single-valued solution concepts, first and foremost, the Deegan-Packel index (cp. Definition 3.25) and the Banzhaf-Penrose index (cp. Definition 3.24) do not meet the fairness requirement. What is more, they do not fit the characteristics of SVNs in other points either. In their original domain of simple (voting) games, the Shapley-Shubik index and the Banzhaf-Penrose index are monotonic with respect to the voting weights. That is, individuals with a higher voting weight are assigned a greater or equal Shapley value, or Banzhaf-Penrose index, respectively. The Deegan-Packel index does not yield this property [161, 160]. When it comes to judging voting power, this characteristic is said to be highly preferable as it supports the intuition that more votes should not lead to a smaller value as inherently possible when applying the Deegan-Packel index [248, 123]. The Banzhaf-Penrose index significantly differs from the Shapley-Shubik index (and therefore, the Shapley value) in terms of its interpretation of a priori power [124]. The Banzhaf-Penrose index reflects a clear probabilistic notion as it is an a prior probability of that an individual is pivotal, that is, making a winning coalition a losing one and vice versa [125]. In other words, it refers to an individual's influence upon the decision made by a coalition of agents. On the other hand, the Shapley value represents the expectation of the share that an individual can take from the result of the cooperative decision, yet based on its individual action. Again transferred to the scenario at hand, the latter notion is preferable since it reflects the way joint value is actually created and distributed in SVNs. Therefore, Shapley-style calculus is proposed as the preferred underlying metric to the power ratio.

Due to the structure of SVNs, some variants of the originally presented Shapley value [292] do not apply: neither do we face a game where the individual agent can be neglected nor is it possible to install sophisticated bargaining procedures (cp. Section 3.2.1.3). Particularly in the context of SVNs, the ad-hoc creation of rather short-lived complex services is a key feature (cp. Section 2.2), such that bargaining procedures (resulting in the Shapley value as a non-cooperative equilibrium outcome) cannot be implemented. Further, due to the very importance of single services in early SVNs, the non-atomic version of the Shapley value designed for large populations is not applicable.

However, the Shapley value is originally defined on coalitions, that is as to SVNs, a basic assumption would be that service providers are able to cooperate with any other vendor in the network. This does not hold for SVNs due to their sequence-sensitivity (as formally introduced in Section 2.2.3). As extensively discussed in Section 3.2.1.4, Myerson [233] attached the Shapley value with an underlying network structure (cp. Definition 3.27). Inherited from the Shapley value, the Myerson value assumes superadditive value functions (cp. Definition 3.19). The application of superadditive value functions in solution concepts cannot handle situations with smaller cooperations obtaining a certain goal as efficient as or even more efficiently than larger ones. The player-based flexible network rule (PBFN) presented by Jackson [170] overcomes this issue by introducing monotonic covers of value functions (cp. Definition 3.28). However, other than the PBFN, the power ratio shall exclusively include the SVN as it is made available to satisfy a specific customer demand while the PRTF considers connections as they could *potentially* be formed. The focus of the PR is limited to the linkage structure as present in G, that is, the allocated path as well as *actually available* alternatives thereof.

In this connection, a valuation must always occur at a complex service level since only complex services that include each functionality demanded by the customer are able to create value. However, as stated in the cooperational monotonicity requirement (cp. Requirement 4.5), an increase in an individual's efficiency must at least provide the same or a higher PR transfer. The actual fulfillment of the latter needs to be evaluated, the same holds for fairness: the original form of the Shapley and

Myerson value are in fact fair and coalitionally monotonic[4], yet the modifications made in the power ratio require a reassessment of these properties.

4.3 Related Work

This section specifies research approaches which are closely related to the work at hand and highlights their issues and shortcomings that are addressed in this thesis. As academic research on service value networks is in its infancy, directly related academic contributions are scarce. However, the related work can be roughly classified into four categories. First, mechanism design approaches in relevant domains, that is, in environments that exhibit features of SVNs, are focussed on. Second, multi-attribute procurement auctions are reviewed due to their fit in terms of the auction type. Third, the co-opetition mechanism is distinguished from Shapley mechanisms which are related as to their application of the Shapley value to mechanism design. Finally, allocation rules from network design are related to the co-opetition mechanism in terms of value distribution.

Mechanism design in the Web service domain

A line of research that is closely related to this approach is presented in Blau et al. [48, 47, 46], Blau [45]. Basically, two different mechanisms to coordinate complex service allocation and to determine their prices in service value networks are discussed. The Complex Service Auction (CSA) as an allocative efficient and dominant strategy incentive-compatible VCG-based mechanism, is geared to fulfill the classic mechanism design desiderata. The other side of the coin is its susceptibility to overpayments, which can be severe. Further, the CSA disregards network requirements such as growth or interconnectedness that are particularly important in the launch phase of an SVN. The Interoperability Transfer Function (ITF) as an extension of the CSA limits overpayments in order to satisfy budget balance constraints. By also setting incentives for increasing interoperability of services, the ITF can be seen as a first approach to network-related properties.

The sequence of service modules within a composite Web service is also considered in the combinatorial auction presented in Mohabey et al. [228]. As service quality attributes are included as well, this mechanism allows for an allocation that is based on the fit of the requester's preferences and the quality level of the services. Incorporating budget constraints, the mechanism sacrifices incentive compatibility. However, Mohabey et al. [228] do not consider the peculiarities of co-opetitive environments such as SVNs.

Stösser [306] presents a double-sided market mechanism for trading Grid resources which approximates the optimal solution in order retain computational tractability. Two different pricing schemes are presented that deal with the trade-off between strategic behavior and computational complexity, making the mechanism applicable in large-scale settings. Due to its application area, the approach neither

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[4] As mentioned in Requirement 4.5, this property is originally called "coalitional monotonicity" with respect coalition-based cooperation structures [340].

yields sequence-sensitive service composition support nor considers complex QoS characteristics.

Schnizler [288] considers the trade of multiattribute Web service bundles in a combinatorial auction. The MACE (Multi-Attribute Combinatorial Exchange) mechanism allows for the bundled trade of infrastructure resources that can be described via rudimentary service attributes. MACE does not support service compositions whose sequence must be considered as it is the case in SVNs. An extension of MACE presented by Lamparter and Schnizler [203] introduces semantically describable quality attributes, thereby allowing for complex QoS support.

In total, the above-mentioned approaches do not reflect important properties to be met in the formation phase of a service value network. An exception and first step into the direction of networked mechanism design is the ITF in Blau [45] which includes interoperability as an additional design goal.

Multiattribute procurement auctions

In terms of the applied methodology, reverse multiattribute auctions (procurement auctions) should be classified the closest related type of mechanism.[5] They allow for the negotiation over non-price attributes that determine the optimal allocation.

Parkes and Kalagnanam [259] introduce models for iterative procurement auctions that focus on classic mechanism design objectives. Moreover, efforts are put into retaining some of the sellers' private information. Building thereupon, Engel and Wellman [112] propose a multiattribute mechanism that focusses on preference elicitation and computational issues, allowing for an adequate expressiveness in multiattribute applications and, at the same time, preserves the buyer's privacy of information. Both scholars put dedicated effort into limited information revelation. Thus, these articles pursue different goals than the co-opetition mechanism. Further, due to the very basic procurement scenario that is non-networked and non-service related, the models neither support compositions and sequences of services nor network objectives.

Bichler and Kalagnanam [38] discuss characteristic winner determination problems in multiattribute auctions. Akin to the co-opetition mechanism, their model allows for configurable offers on seller-side. However, focus is put upon formulating and solving allocation problems from an operations research perspective. That is, Bichler and Kalagnanam [38] deal with optimization and largely ignore mechanism design issues.

Applying an optimal auction approach, Ronen and Lehmann [277] present a mechanism that approximately maximizes the auctioneer's utility in a two-stage VCG-based approach while retaining computational tractability. Just like in the above-listed procurement auction approaches, network design objectives as well as an adaptation to the Web service domain do not play any role. On the same lines, Beil and Wein [32] propose a multiround procurement auction that optimizes the requester's utility. Their approach shows a general shortcoming of procurement auction approaches in consideration of their application in SVNs: they assume sophisticated, long-term relationship settings that may include several negotiation steps.

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[5] In Section 5.1.1, procurement auctions are discussed in more detail.

While the variety of attributes is also present in SVNs, relations are much more dynamic such that transactions are (*i*) likely to be non-recurring and (*ii*) their overall value is usually too low to justify the implementation of complex iterative processes that require increased communication efforts.

Shapley value mechanisms

The Shapley value mechanism as presented by Moulin and Shenker [230] is related to this work in terms of its value distribution logic. The Shapley value mechanism addresses a distinct problem: how to allocate a service (or similar) to a set of agents with different valuations and how to distribute the costs of providing the service to the agents? The most prominent application scenario of the Shapley value mechanism is multicast cost sharing which allocates a transmission to a set of agents in a network of costly links and determines the charges collected from the receivers (cp. e.g. [119, 230, 212]). In more detail, the transmission flows through a multicast tree whose links have associated costs $\tilde{c} \geq 0$ and whose nodes symbolize the potential receivers of the transmission. The latter exhibit a utility for receiving the transmission [121].

The Shapley value mechanism can be seen as a special case of of the Shapley value (cp. Section 4.2) as the cost of a link is shared adequately by all receivers who are downstream of the link [119].[6] Therefore, the Shapley value mechanism can be classified as fair. Further, the mechanism is strategy-proof and budget balanced, however, lacks efficiency. It is important to note that the links are assumed to be obedient, that is, link costs are known and not subject to strategic behavior which is only assumed at receiver-side. In this regard, the Shapley value mechanism does not fit the application of the co-opetition mechanism.

Further, in contrast to a the co-opetition mechanism, the Shapley value mechanism only includes allocated agents into the transfer function.

Solution concepts in network games

Apart from mechanism design approaches, solution concepts in network games deal with the distribution of value or costs, respectively, without considering strategic behavior regarding the participants' types. Moreover, such solution concepts are usually domain neutral, which is, for instance, reflected in very general underlying network models. The network-based solution concepts presented by Myerson [233] (Myerson value) and Jackson [170] were extensively discussed in Sections 3.2.3 and 4.2. Both solution concepts distribute value in networks based on Shapley-style calculus and can be classified as fair. Therefore, the concepts by Myerson [233] and Jackson [170] are highly relevant in terms of the co-opetition mechanism's transfer function since they allow for a distribution of value according to participants' marginal contributions to the network's value. However, they exhibit entirely different focal points: concentrating on how value in network games is assigned to

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[6] In more detail, based on the reported utilities of the potential receivers, nodes are recursively pruned whenever the charged price exceeds the agents' utility. For more details on the algorithm, please refer to Feigenbaum et al. [121], Shoham and Leyton-Brown [296].

individuals, the mechanism design perspective does not apply. Further, there is no provision for an application to a specific domain such Web services and SVNs.

Related to the listed solution concepts, Dutta and Jackson [104] give valuable insights into link formation in one-sided networks which is highly relevant for the interconnectedness which is required in this work. The focus of the paper is on whether the incentives of individuals to add or sever links can lead to pareto efficient networks, thereby applying different allocation functions. Other than that, no specific points of contact to the co-opetition mechanism and its properties can be stated.

Recapitulation

It is difficult to utilize the same measures to appraise the above-listed contributions to literature since they come from entirely different starting points. While Blau et al. [48], Blau [45] is certainly the closest related work, operating on the same formalization of Web service markets as this thesis (cp. Section 2.2), other approaches cannot be simply transferred to the SVN scenario, in which not only QoS (covered by multiattribute procurement auctions), but also the component services' sequence plays a crucial role. What is more, none of the related work considers network design objectives to the extent that is required in the starting phase of a co-opetitive environment. The literature demonstrates that the co-opetition mechanism's main distinguishing factor is its support of network design goals.

On top of the presented lines of research, service composition is also considered from a technical perspective. Zeng et al. [344] account for both QoS characteristics and sequence-sensitive service compositions, however, assume complete information about the participants' types. Their maximization approaches are based on linear programming methods and do not account for any strategic behavior based on individual utilities. Thus, the mechanism design perspective does not apply.

In Table 4.1, the most relevant related literature is listed and rated according to its degree of satisfaction regarding the co-opetition mechanism's requirements stated in Section 4.1.[7] Additionally, other requirements from classic mechanism design as well as computational tractability are also inserted into the list. Requirements are sub-divided into network design goals, classic mechanism design desiderata, and applicability requirements.[8] Note that it is not reasonably possible to classify each of the above-mentioned approaches due to their heterogeneity.

4.4 Summary

In this chapter, the basic idea of both the co-opetition mechanism and its novel concept of value distribution – the power ratio – were discussed and accounted for in detail. Taking a network operator's point of view, it is essential to sustainably attract participants in order to establish a functioning business. Thus, incentive engineer-

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[7] Uniqueness as a quite straightforward requirement and cooperational monotonicity are deliberately omitted in Table 4.1. The latter is closely related to fairness and is thus not listed separately.

[8] In Table 4.1, *MD* shall stand for mechanism design. *Applic.* abbreviates applicability requirements.

Table 4.1: Requirements satisfaction degree of related approaches (● = fully satisfied, ◐ = partly/approximately satisfied, ○ = not satisfied/ not applicable).

		Network growth	**Readiness**	**Fairness**	**Interconnectedness**	**Budget balance**	**Individual rationality**	**Incentive compatibility**	**Allocative efficiency**	**Sequence of complex services**	**Complex QoS support**	**Computational tractability**
		Network design				*Classic MD*				*Applic.*		
Approaches	Blau [45] (CSA)	○	○	○	○	○	●	●	●	●	●	●
	Blau [45] (ITF)	○	○	○	◐	●	●	◐	◐	●	●	●
	Mohabey et al. [228]	○	○	○	○	●	●	○	○	●	●	○
	Stösser [306]	○	○	○	○	●	●	◐	○	○	○	●
	Schnizler [288]	○	○	○	○	●	●	○	○	○	◐	○
	Lamparter and Schnizler [203]	○	○	○	○	●	●	○	○	○	●	○
	Parkes and Kalagnanam [259]	○	○	○	○	●	●	◐	◐	○	◐	◐
	Moulin and Shenker [230]	○	○	●	○	●	●	●	○	○	○	●
	Myerson [233]	○	○	●	○	●	○	○	○	○	○	○
	Jackson [170]	○	○	●	○	●	○	○	○	○	○	○
	Zeng et al. [344]	○	○	○	○	●	○	○	○	●	●	●
	This work	●	●	●	●	●	●	◐	◐	●	●	○

ing plays a crucial role. Mechanism design can tackle this challenge. However, the SVNs as a particularly co-opetitive and networked environment requires a modification of the classic mechanism design notion towards a networked variant called NMD in which objectives from network design and cooperative game theory take a central role, partly eclipsing classic economic desiderata.

This notion is reflected in the social choice of the co-opetition mechanism. The bulk of requirements to be fulfilled are owed to the networked environment and its co-opetitive nature (cp. Requirements 4.1 to 4.6). Applicability requirements shall insure a perfect fit to SVNs. Summed up, these objectives lead to a partial constriction of classic mechanism design desiderata. While budget balance and individual rationality are retained in order to make the mechanism viable in practice, incentive compatibility and allocative efficiency are not explicitly aimed at, however, in selected network configurations, the degree of strategic manipulation is clearly limited as will be shown in Section 7.1.

The essence of the power ratio can be summarized as follows: payments are not only granted to service owners whose services are actually allocated in a specific complex service, but also to potential creators of value. Thereby, the PR grants a percentage of the overall value to be distributed to service providers that keep ready their resources. The payment is based upon Shapley-style calculus, containing elements from the extension of the Shapley value to networks. By definition, the PR inherently meets Requirements 4.2 (Readiness) and 4.4 (Uniqueness) as will be taken up in Chapter 5.

Based on a comprehensive overview on related work, the co-operation mechanism can be mainly differentiated from four partly heterogeneous fields of research, three of which are related to mechanism design. First, academic literature recently started to deal with mechanism design in the relevant field of Web service markets. Second, multiattribute procurement auctions are related in terms of the auction type applied. Third, Shapley value mechanisms incorporate the same concept of value (or cost) distribution. However, most of the approaches ignore network design goals and applicability for composed and sequence-sensitive service mashups. The forth line of related research, network games that evolved from solution concepts from cooperative game theory, fit in terms of the Shapley-style distribution of value and the coinciding fairness property, yet mechanism design issues and application to service networks are not part of their scope.

Finally, it remains to be noticed that, in Chapter 4, two of the research questions of this thesis were addressed. Firstly, in conjunction with the mechanism and network design foundations given in Sections 3.1.4 and 3.2.3, classic mechanism design was mapped to networked objectives, resulting in the networked mechanism design perspective (cp. Research Question 2). Secondly, based on Sections 3.1.3 and 3.2.3, the design objectives of the co-opetition mechanism tailored to suit the requirements of service value networks in their starting phase were surveyed (cp. Research Question 3).

Chapter 5

The Co-Opetition Mechanism

Weinhardt et al. [329] and Neumann [240] state that there is no general mechanism available to fit any possible market setting. In accordance with this well-established principle, it is necessary to present a suitable mechanism designed to fit the underlying field of application. The adequacy of a mechanism depends, amongst others, on the properties of the trading objects. In SVNs, the latter are modular Web service components as well as the composed complex services resulting thereof. There characteristics were discussed in detail in Chapter 2.

Recall that mechanism design is a subfield of game theory that takes over an engineering perspective [243]. The goal of the mechanism is manifested in a social choice function that reflects the design objective. The work at hand is concerned with establishing a functioning business in an early formation phase of a service value network. In a comprehensive environmental analysis (cp. Section 4.1), requirements for SVNs in their launch phase were set out.

Section 5.1.1 will briefly describe why an *auction mechanism* is particularly suited to tackle complex service coordination in distributed environments. Delving deeper, there are three fundamental components in the design of an auction mechanism [242, 257]. The *bidding language* (cp. Section 5.1.2) provides an instrument to formalize pieces of information that are exchanged between the mechanism and its participants (service customer and service providers). Participants in the SVN are decentralized and act opportunistically according to their self-interest subject to the necessity to engage in joint value creation. Both parties in SVNs, service customers and service providers, hold private information on their type – the former in respect of their preferences for the specific service requested, and the latter concerning their costs and ability to provide services at a certain quality level.

The information objects disclosed via the bidding language are exchanged during the conduction of the auction which consists of the *allocation function* (cp. Section 5.2.2) and the *transfer function* (cp. Section 5.2.3). The allocation function mainly comprises an algorithm to determine the component services that are included in the complex service according to a defined maximization rule. In other words, the mechanism operator has to solve the problem of allocating a path that connects selected service offers within the SVN, thereby maximizing a predefined goal function. Money flows exchanged between participants of the mechanisms, which compensate service providers for their actual costs and set incentives that enable the system to obtain a "good enough" solution, are determined by the mechanisms' transfer function.

After presenting the core mechanism, the co-opetition mechanism's realization in terms of algorithmic implementation rounds off this chapter. Section 5.3 also includes a complexity consideration and the architecture of the agent-based simulation tool that will be applied to evaluate the mechanism in Part III of this thesis.

5.1 Service Selection Via Auctions

As we have seen in Section 2.2.4, forerunners of SVNs are already in their starting blocks. However, neither current pricing models nor the fashion of service coordination reflect the agile and distributed nature of the environment the services are traded in. Generally, pricing is static for the most part, at best allowing for price discrimination, for instance, with respect to the volume of services traded.[1] Such static pricing does not include situational preferences of service providers.

In related domains, companies have already discovered the potential of auctioning their offerings. Auctions are said to perform particularly well in settings where heterogenous and intangible trading objects are exchanged [300]. For instance, this potential is taken advantage of by Google with its advertising service AdWords[2]. In order to price and allocate ad space, they apply a generalized second-price auction which incorporates a quality score to classify advertisements [322]. According to Edelman et al. [107], this ad auction generated 98% of Google's 2005 revenues.

Recently, the auctioning of services has gained mainstream acceptance with Amazon's EC2 Spot Instances[3]. EC2 Web service capacity that is not directly sold via Amazon's traditional price model can be bought at an auction. As long as a customer's bid exceeds the current spot price, the EC2 instance can be run. The spot price changes periodically based on actual supply and demand. Certainly, termination of used instances is rather unpredictable, however, the model supports customers that are flexible in terms of execution time. This is a remarkable example of how service providers exploit (one-sided) auction settings in order to catch quickly changing demand, in Amazon's case, optimizing their capacity utilization.

Section 5.1.1 will focus on an analysis of the applied auction setting in SVNs, namely multiattribute reverse auctions, thereby cautiously forgoing a general overview on auction theory.[4] Customized to our setting, Section 5.1.2 presents the bidding language that is designed for the co-opetition mechanism. Further, the auctioning process of the co-opetition mechanism is briefly sketched in Section 5.1.3.

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[1] For example, StrikeIron offers volume discounts if a larger number of Web service usages is purchased.

[2] `http://adwords.google.com/`

[3] `http://aws.amazon.com/ec2/spot-instances/`

[4] A comprehensive overview on auction theory can be found in Klemperer [189], Milgrom [227].

5.1.1 Procurement Auctions in Service Markets

As introduced in Section 2.2, customers approach the service value network with the objective of procuring a complex service that is tailored to their requirements. While it maybe possible to procure simple kinds of services "off-the-shelf" by only negotiating along one dimension – the price – without specifying any attributes that configure and fix quality of service, this is certainly not true for the kind of complex services traded in service value networks. Therefore, the trading in SVNs should be described by means of a *multiattribute procurement auction*.

In *single-sided reverse procurement auctions*, a single buyer (the service customer) receives bids from multiple competing sellers [37, 178, 189]. *Multiattributivity*, as introduced to auction design by Che [70] and Branco [53], allows for the negotiation over non-price attributes by referring to multiple features of a single unit [331].

In Web service scenarios, multiattribute approaches that allow for the negotiation over various non-price attributes that constitute a service's configuration is of crucial importance. Particularly in SVNs, where complex services are assembled from complementary service offerings, a multitude of different service configurations must be handled and aggregated, adding up to a potentially great variety of complex services offering different QoS. For each of these configurations, the buyer has a (most likely different) valuation. On this basis, procurement auctions determine which service providers are to win the auction, which service configuration has to be provided by them, and which payment has to be made by the service customer. Importantly, multiattribute procurement auctions allow different service providers to compete over both attribute values and price. This is a particularly important feature in the service world where quality has become the main differentiator thanks to quickly decreasing ICT costs and harsh price competition [216, 90, 256].

Due to their complexity, procurement negotiations on multiple services and on services with multiple attributes have traditionally been conducted manually as request for quotes (RFQ) or via phone negotiations [41]. However, in the last decade, electronic auctions in procurement settings have emerged and proven to suit the problem set remarkably well: today powerful computer networks have brought up electronic marketplaces that can handle the procurement of multiattribute services through automated negotiation and the determination of the winning complex service [39, 68, 41].

Beall [31] surveyed that by as early as 2002, electronic reverse auctions were used for an average of approximately 4% of the polled companies' total spend. Larger companies already use procurement auctions for more than 25% of their spend. These numbers were expected to exhibit distinct growth in the following years. Currently, procurement auctions are mainly applied by companies that seek to optimize their procurement activities, relying on commercial software as for example provided by Ariba[5] or i2 Technologies[6]. Thus, the mechanism operator, or auctioneer, respectively, and the buyer coincide. However, with emerging marketplaces such as SVNs and due to the power of combinatorics of modular Web services and the effects of the long valley, a procurement mechanism offered to "third party

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[5] `http://www.ariba.com/about/`

[6] `http://www.i2.com/`

buyers" becomes more and more interesting as a rule set and framework to enable transactions. Such third party buyers are customers interested in procuring complex services via a service marketplace.

Academia and practice have brought up different variants of procurement auctions. Besides the multiattribute character, procurement auctions can either be designed for single-unit or for multi-unit settings. In the latter, sellers bid for bundles and/or are given the possibility to negotiate over volumes [39, 68]. This is not the case in SVNs where quality, not quantity is in focus: service customers request only one complex service that is *technically interpreted as a single item*. That is, the winning complex service is in fact assembled from the offerings of diverse service providers, yet the set of required service components and its sequence is fixed. Exactly one component service out of each candidate pool will be chosen to add up to the complex service requested. Different customer valuations for bundles of services, for instance, one bundle comprising a service from candidate pools Y^1 and Y^2 and a second bundle including services from Y^2 and Y^3, are not applicable since the buyer will only procure a complex service that includes a defined sequence of services (e.g. consisting of the candidate pools Y^1, Y^2, and Y^3, in exactly this sequence), otherwise its valuation is zero. Thus, a variety of different services is available in the same market, however, the customer's valuation and its bidding language is less complicated than in a typical combinatorial auction setting.[7] Transferred to SVNs, multiattribute auctions allow for expressing preferences over configurations of a specific complex service rather than over bundles of services as supported by combinatorial approaches [113].

In general, the reverse character of procurement auctions with multiple units being allocated can lead to situations where the valuation on the buyer-side (i.e., the service customer in the SVN setting) is less than the total payments to be made to the sellers (i.e., service providers) [195]. Parkes and Kalagnanam [259] state that the multiattribute allocation problem with a single buyer belongs to settings with two-sided private information. This complicates the determination of the allocated service providers since, besides the private seller types, market clearance additionally depends on the revealed preferences of the buyer. Therefore, this setting can be interpreted as a generalization of a single unit, one buyer and one seller bargaining setting [195]. In such a setting, the Myerson-Satterthwaite [239] impossibility theorem (cp. Therorem 3.1) holds.

In the next section, a bidding language for both service customer and service provider is introduced which fully captures the multiattribute nature of negotiating the procurement of complex services in SVNs.

5.1.2 Bidding Language

During auction conduction, information needs to be exchanged between the involved parties. In the following, a bidding language is introduced that is based on bidding languages for products with multiple attributes [113]. The formalization is aligned to recent work in multiattribute auction theory [259, 277]. Further, it as-

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[7] Combinatorial auctions are not assessed in more detail in this thesis. For a comprehensive overview of this kind of auction setting, please refer to Cramton et al. [88].

sures compliance with the WS-Agreement specification to enable a realization in the Web [11].

The consumer's request is not only represented by the very service functionality demanded, but also by the service configuration $\mathcal{A}_{F_l}$ of the complex service $F_l \in F$.[8] The configuration $\mathcal{A}_{F_l}$ of the complex service is the aggregation of all $\tilde{m}$ attribute values of contributing services in F_l such that $\mathcal{A}_{F_l} = (\mathcal{A}^1_{F_l}, \ldots, \mathcal{A}^m_{F_l}, \ldots, \mathcal{A}^{\tilde{m}}_{F_l})$ with $\mathcal{A}^m_{F_l} = \oplus_{v_j \in W_l} a^m_j$. The aggregation operation $\oplus$ of attribute values depends on the characteristics of the respective non-functional property. Different exemplary aggregation functions for service attributes are presented in Table 5.1.

Table 5.1: Attribute-dependent aggregation functions

Attribute type	**Aggregation function**
Response time *(rt)*	$\sum_{v_j \in W_l} a_j^{rt}$
Availability *(av)*	$\prod_{v_j \in W_l} a_j^{av}$
Reputation *(rp)*	$\frac{1}{\lvert Y \rvert} \sum_{v_j \in W_l} a_j^{rp}$
Throughput *(tp)*	$\min_{v_j \in W_l} a_j^{tp}$

Response time is the time that elapses between service invocation and response after having successfully completed the task. Since component services within a complex service are built upon each other, the sum operator needs to be consulted. Availability is defined as the probability that a service is accessible. Therefore, these values have to be multiplied in order to compute $\mathcal{A}^{av}_{F_l}$. Reputation can be interpreted as the ranking of a complex service which is typically specified by averaging the reputation of the involved component services [344]. Throughput is the measure for the amount of data that can be processed by a service per time unit, therefore the component service yielding minimal throughput is usually the bottleneck with respect to the complex service.

The list of aggregation operations in Table 5.1 is not intended to be exhaustive. As shown in Blau [45], the bidding language also supports more complex aggregation operations such as logical connectives. The attribute "encryption" is a simple example, which is aggregated via conjunctions. Assuming that services can exhibit different encryption algorithm types while the requester demands a special format, semantic subsumption can be consulted to asses which service components, and consequently, which complex services fit the customer's request. Such complex QoS aspects are briefly covered in Section A.1. In excess thereof, the interested reader is referred to Lamparter [201], Blau [45].

Basically, the customer defines the very functionality demanded and the service attributes of interest to be included.[9] Comparability of attribute values from different attribute types is ensured by introducing a mapping function Ψ to normalize the attribute values $\mathcal{A}^m_{F_l}$ to an interval [0;1]. Such a normalization is required to assess the degree of correspondence of F_l to the service con-

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[8] Recall from Section 2.2.3 that complex services are defined as a tuple $F_l := (W_l, E(W_l))$.

[9] For example, by choosing from a range of possible attributes to be factored into the complex service allocation via an appropriate interface (cp. also Section 8.3).

sumer's request. The service customer specifies lower and upper boundaries $\Gamma = ((\gamma_B^1, \gamma_T^1), \ldots, (\gamma_B^m, \gamma_T^m), \ldots, ((\gamma_B^{\tilde{m}}, \gamma_T^{\tilde{m}}))$ for each attribute type m. γ_B^m denotes the value of attribute m that results in a zero valuation whereas γ_T^m represents the value of attribute m that yields a maximum fit of 1. If $\mathcal{A}_{F_l}^m \geq \gamma_T^m$, then $\Psi(\mathcal{A}_{F_l}^m) = 1$. Vice versa, $\Psi(\mathcal{A}_{F_l}^m) = 0$ if $\mathcal{A}_{F_l}^m \leq \gamma_B^m$. $\Psi(\mathcal{A}_{F_l}^m)$ is typically assumed to be linear between the upper and lower boundary, yet could also take any other kind of coherency. Importantly, the valuation takes place on a complex service level, the customer is not interested in the performance of a single service, but merely in the QoS of the complex service requested.

Further, the customer-specific weighting $\Lambda = (\lambda_1, \ldots, \lambda_m, \ldots, \lambda_{\tilde{m}})$, $\sum_{m=1}^{\tilde{m}} \lambda_m = 1$ is reported, defining the requester's preferences for each attribute type. This coherency is depicted in the requester's scoring function $\mathcal{Q}$ which includes all non-monetary dimensions of the service and maps them onto a single value [16]. That way, in accordance with Che [70], the scoring rule is designed by the service requester:

$$\mathcal{Q}(\mathcal{A}_{F_l}) = \sum_{m}^{\tilde{m}} \lambda_m \Psi(\mathcal{A}_{F_l}^m) \tag{5.1}$$

The customer's maximum willingness to pay for a perfect complex service α is the last piece missing in order to fully describe the offered services' fit to the customer's preferences. α is the reservation price for a complex service yielding a score of 1. Altogether, α, the defined weighings Λ, and the customer-specific lower and upper boundaries Γ for each service attribute type constitute the customer type $\theta \in \Theta$ with $\theta = (\alpha, \Gamma, \Lambda)$.

Definition 5.1 [Multiattribute service request]. *A multiattribute service request for a complex service is a vector defined as follows:*

$$SR := (Y^{SC}, \underbrace{\alpha, \Gamma, \Lambda}_{\theta}) \tag{5.2}$$

Y^{SC} represents the desired functionality of the service stated in a suitable format specified by the platform. The maximum customer's willingness to pay for an optimal service configuration is denoted by α. Γ stands for the lower and upper boundary for each attribute type. Finally, Λ represents the requester's preferences for the relevant service attributes.

For simplicity, assume that the service customer states the requested functionality Y^{SC} in the form of the previously introduced candidate pools $(Y^1, \ldots, Y^k, \ldots, Y^{\tilde{k}})$, with the order of the elements in Y^{SC} indicating the order of the services included in the complex service demanded. Of course, the format specified by the platform can be different, however, is then to be mapped to the candidate pool logic introduced in Section 2.2.3. α multiplied by $\mathcal{Q}(\cdot)$ defines the substitution rate between a complex services' configuration and the requester's preference.

As soon as the requested functionality has been submitted to the platform intermediary, potential services belonging to the respective candidate pools are contacted. As a response, service providers willing to participate in the bidding submit their service offers to the intermediary.[10] Service offers consist of a service configuration $\mathcal{A}_j$ and a price bid submitted for a service v_j as successor of v_i. In other words, service providers bid to be included in the complex service dependent on the respective preceding service v_i.

Definition 5.2 [MULTIATTRIBUTE SERVICE OFFER]. *A multiattribute service offer submitted by a service provider n_h with respect to one of its services v_j, $\bar{\sigma}(v_j) = n_h$, consists of an offered functionality Y^k and a bid $b_{ij} \in \mathcal{B}$ with $b_{ij} = (p_{ij}(e_{ij}), \mathcal{A}_j)$, $v_j \in Y^k$, $v_i \in Y^{k-1}$, $k \in \{1, \ldots, \tilde{k}\}$:*

$$SO_{ij} := (Y^k, \underbrace{p_{ij}(e_{ij}), \mathcal{A}_j}_{b_{ij}}) \tag{5.3}$$

A service provider n_h can submit more than one service offer: both interoperability with more than one service predecessor and the ownership of more than one service that fits the service request result in a set of service offers $SO_h = \{SO_{ij} | \bar{\sigma}(v_j) = n_h,\ v_j \in Y^k,\ v_i \in Y^{k-1},\ k \in \{1, \ldots, \tilde{k}\}\}$. The set of all service offers submitted (that lead to the customer-specific SVN G including each of the requested functionalites Y^{SC}) shall be denoted as SO^G.

To summarize, the multiple service attributes are known a priori and are uncorrelated. As supported by the customer's upper and lower boundaries Γ of considered attribute values and the mapping function $\Psi(\cdot)$, each attribute can take an individual value from a domain of possible values for the attribute, both on customer- and on provider-side [68]. In total, the multiattribute support of the bidding language and the integration of rule-based semantic description techniques[11] allows for the specification, aggregation, and management of complex quality of service requirements and offerings.

Example 5.1 [BIDDING LANGUAGE AND SCORING FUNCTION]. *The following example illustrates how different attribute types are aggregated along a path of composed service offers in SVNs. It further shows how the set of weights Λ and the upper and lower boundaries Γ are processed in the calculation.*

Consider a mid-size company named uServ which seeks to purchase a "service request and order management service" that supports its complex customer relationship business process. The company therefore approaches an SVN, inquiring a solution that (i) handles service requests and orders in a first step (Y^1) and (ii) afterwards confirms the orders (Y^2). Further assume that, besides this very functionality Y^{SC}, uServ is mostly concerned with the availability (av) of the service and its throughput (tp), valuing both attributes equally ($\Lambda = \{0.5, 0.5\}$). Additionally, uServ defines upper and lower boundaries for av and tp in a certain unit, in this example, assume $\Gamma = ((0.98, 1), (75, 125))$, with γ_1 being measures in percentage, i.e. 0.98 equals 98% availability, and γ_2 being measured in Megabits-per-second (Mbit/s). As uServ is willing to pay $\alpha = 100$ Euros for a defined amount of

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[10] A more detailed description of the information exchange taking place between the involved parties can be found in Section 5.1.3.

[11] Cp. also Section A.1 and Blau [45].

usages, uServ's type assembles as $\theta = (100,((0.98,1),(75,125)),\{0.5,0.5\})$*, leading to* $SR = \big((Y^1,Y^2),\theta\big)$.

The platform operator processes uServ's service request as illustrated in Figure 5.3, resulting in five service offers SO^G*. Exemplarily, service provider* n_3*'s set of service offers* SO_3 *assembles as* $SO_3 = (SO_{13},SO_{23})$ *with* $SO_{13} = \big(Y^2,20,\{0.998,110\}\big)$ *and* $SO_{23} = \big(Y^2,33,\{0.998,110\}\big)$*. For the other service offers, please refer to the graph G depicted in Figure 5.1.*

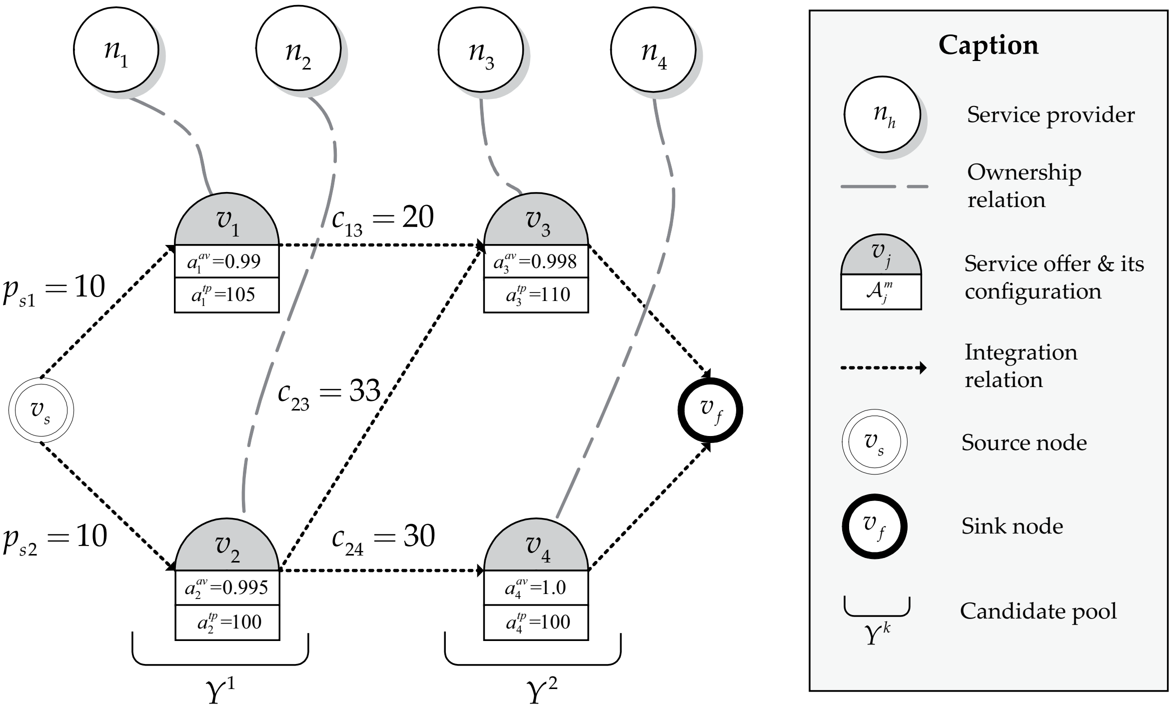


Figure 5.1: Numerical example of a service value network

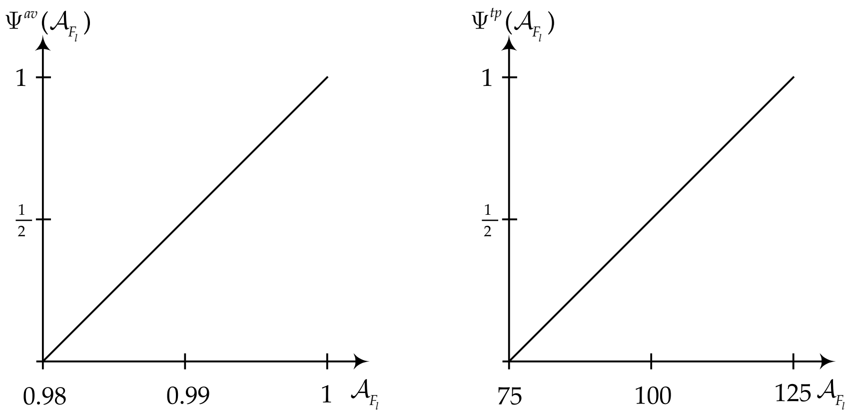
G yields three instantiations: service v_1 *combined with service* v_3 *as the first possibility, service* v_2 *and service* v_3 *as the second alternative, and finally a composition of service* v_2 *and service* v_4*. So, the set of paths F is defined by* $F = (F_1,F_2,F_3)$ *with* $F_1 = (\{v_1,v_3\},\{e_{s1},e_{13}\})$, $F_2 = (\{v_2,v_3\},\{e_{s2},e_{23}\})$*, and* $F_3 = (\{v_2,v_4\},\{e_{s2},e_{24}\})$.

As stated earlier and illustrated in Figure 5.2, it is assumed that the mapping function is linear between the upper and lower boundary such that $\Psi(\mathcal{A}_{F_l}^{av})$ *and* $\Psi(\mathcal{A}_{F_l}^{tp})$ *are defined as follows for each complex service* $F_l \in F$.

$$\begin{aligned}\Psi(\mathcal{A}_{F_l}^{av}) &= \tfrac{1}{1-0.98}\cdot(\mathcal{A}_{F_l}^{av}-0.98)\\ \Psi(\mathcal{A}_{F_l}^{tp}) &= \tfrac{1}{125-75}\cdot(\mathcal{A}_{F_l}^{tp}-75)\end{aligned} \tag{5.4}$$

Equation (5.4) *yields the normalized service configuration. Incorporating* Λ*, the score* $\mathcal{Q}(\mathcal{A}_{F_l})$ *can finally be computed, which peaks for* F_3 *(cp. Equation 5.5).*

$$\begin{aligned}\Psi(\mathcal{A}_{F_1}) = \{0.40,0.60\} &\rightarrow \mathcal{Q}(\mathcal{A}_{F_1}) = 0.5\cdot 0.40 + 0.5\cdot 0.60 = 0.50\\ \Psi(\mathcal{A}_{F_2}) = \{0.65,0.50\} &\rightarrow \mathcal{Q}(\mathcal{A}_{F_2}) = 0.5\cdot 0.65 + 0.5\cdot 0.50 = 0.58\\ \Psi(\mathcal{A}_{F_3}) = \{0.50,0.80\} &\rightarrow \mathcal{Q}(\mathcal{A}_{F_3}) = 0.5\cdot 0.50 + 0.5\cdot 0.80 = 0.65\end{aligned} \tag{5.5}$$



(a) uServ's mapping function for different levels of availability (av)

(b) uServ's mapping function for different levels of throughput (tp)

Figure 5.2: Mapping functions for different attribute types

5.1.3 Auction Process Model

In the preceding sections, details of the auction process and the information exchange between the involved parties were omitted. In this section, the process is shown in more detail. Three generic roles as discussed in Section 4.1 are involved. The service consumer initiates the formation of a specific SVN while the service providers, formerly registered in the pool of available vendors, bid to be included in a customer-driven SVN. Those two sides are brought together to conduct business by the platform operator. The latter takes over the sub-roles of an auctioneer, mechanism operator, and service coordinator.

According to Nisan and Ronen [245], two basic auction phases can be distinguished - the *declaration phase* and the *execution phase*. In the declaration phase, the necessary information to be exchanged among the participants is gathered. These information objects represent the participants' types which are reported in a direct fashion to the intermediary. To be more precise, the service request submitted by the service customer is processed by the platform operator which reasons about potentially fitting services from the pool of registered services, for instance, relying on semantically supported service discovery [249]. Having defined the set of potential services to participate in the mechanism phase, the service intermediary is able to plan and form the actual topology of the SVNs and thereupon sends out a call for bids including additional information on preceding services in order to facilitate context-dependent bidding (cp. Section 2.2.3). This step concludes the preparational activities of the declaration phase and lays the basis for the actual matching – the execution phase.

The execution phase is initiated by the multiattribute service offer submitted by the owners of candidate services which accepted the call for participation. These service offers along with the customer's service request serve as an input for the coopetition mechanism. An automated search for the optimal path through the network according to the allocation function introduced in Section 5.2.2 is followed by the calculation of the transfers among network participants by means of the power-

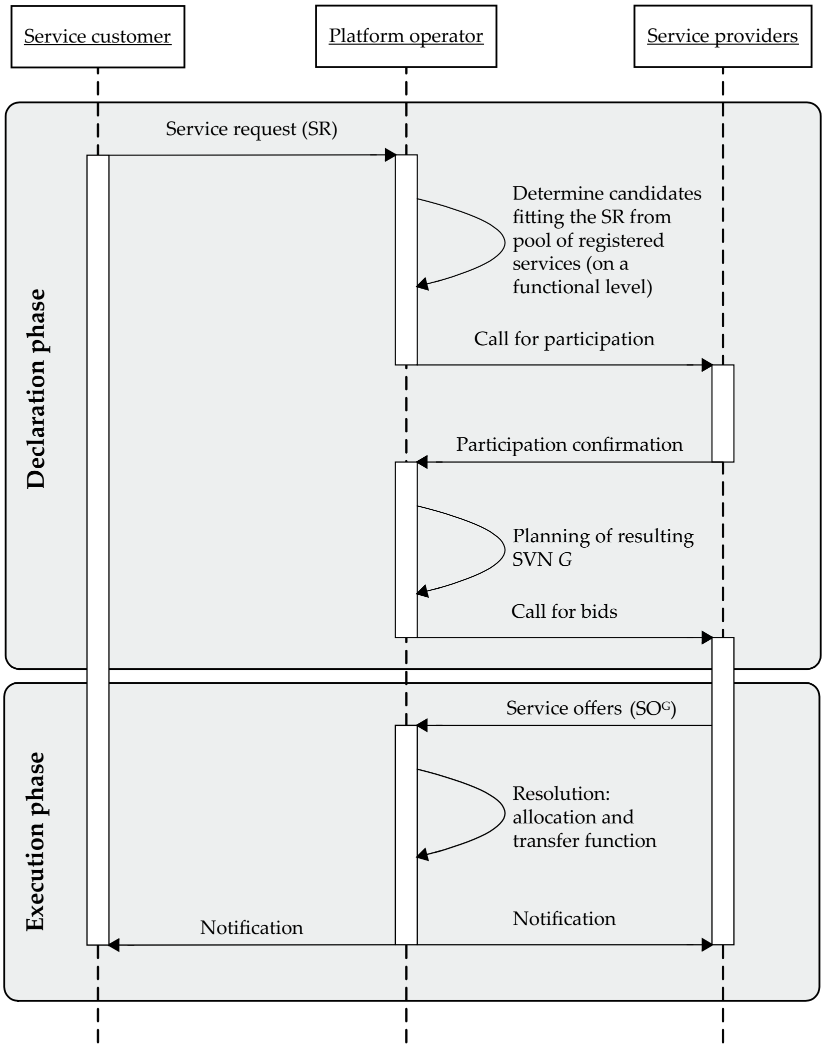


Figure 5.3: Auction process model: Declaration and execution phase. Adapted from Blau [45]

ratio based transfer function (cp. Section 5.2.3). After solving the coordination problem, participants are notified and the actual service delivery (as defined in Section 2.1.2) can be launched. During service delivery (which is cautiously put aside in the process model), monitoring techniques can be applied such that the platform operator can cross check the actual outcome and the reported types of the allocated service providers [283] (cp. also Assumption 5.4 and Section 8.3).

A slight modification of the process shown in Figure 5.3 can be useful in larger networks. As will be shown in Section 5.3.1, the co-opetition mechanism is intractable. This characteristic can be reduced to the transfer function, while the computing the actual allocation and the price charged for the "winning" complex is only a matter of seconds (cp. Table 5.3). Therefore, in order to optimize service delivery, this information may be send out before actually computing the power ratios.

5.2 Mechanism Implementation

Based on the requirements of the social choice defined in Section 4.1, a mechanism is introduced that shall reward service providers based on their marginal contribution to network formation. The mechanism allocates the component services that constitute the winning complex service and distributes payoffs in a manner that is in line with the social choice. This problem shall be solved by the *co-opetition mechanism*.

As the mechanism implementation is based on the abstract model of an SVNs as introduced in Section 2.2.3 and on the bidding language as presented in Section 5.1.2, the co-opetition mechanism is capable of processing service components with due regard for the complex service's sequence (cp. Requirement 4.9) and its QoS characteristics (cp. Requirement 4.10).

5.2.1 Assumptions of the Mechanism

Before presenting the co-opetition mechanism's implementation, its basic underlying assumptions are stated. First, the co-opetition mechanism shall be centralized. That is, the entire communication is directed via the mechanism which connects all agents and is understood as a self-contained (impartial) entity [305].

Assumption 5.1 [CENTRALITY OF THE MECHANISM]. *The service customer and all participating service providers are directly connected to the co-opetition mechanism via a fault- and tap-proof communication channel.*

Second, let us consider the customer-side of the mechanism. In line with a common assumption in literature (cp. e.g. [195, 259, 45]), a straightforward service customer is assumed that will truthfully announce its type to the mechanism. Therefore strategic acting of the customer is not considered.

Assumption 5.2 [STRAIGHTFORWARD CUSTOMER]. *Strategic acting on the customer-side is faded out.*

By the simplifying assumption that the customer reports truthful bids, Theorem 3.1 does not apply any more. That is, if budget balance and individual rationality are to hold, allocative efficiency must not necessarily be given up.

Assumption 5.3 is located at the service provider-side. Since the power ratio distributes payoffs to more than the allocated service providers, free-riding becomes an issue. Service providers could publish "dummy services" which are merely designed to skim power ratios. Therefore, it is required that the services registered with the platform undergo some verification process before they are eligible for inclusion in customer-specific SVNs.

Assumption 5.3 [NO DUMMY SERVICES]. *Service provider cannot publish dummy or mock services that do not exhibit the indicated functionality.*

Finally two general assumptions on the transactions are made. First, consider quality of service. Technically, an agreement between service provider and service consumer about the quality to be delivered must be founded on a legal basis, which is done by specifying a service level agreement (SLA). An SLA is a contract that defines mutual understandings and expectations of a service between service provider and service consumer [180]. As service providers bid their service configuration which is aggregated over the service attributes' values by each service included in a complex service, the resulting QoS denotes the predefined goal to be fulfilled – that is, the service level agreed on. Other than in Blau [45], the co-opetition mechanism does not include an explicit service level enforcement term. It is therefore required that the platform operator can monitor the delivery of a complex service and is able to effectively penalize mal- or non-performance with respect to the SLAs made. That is, service providers that register services with the platform commit themselves to offering the services at the quoted price and quality and can thus legally be "forced" to deliver the stated service configuration. For instance, the monitoring concept applied in TEXO shall be capable of backtracking the responsible services if SLAs are not met (cp. Section 2.2.4.3).

Assumption 5.4 [SERVICE LEVEL ENFORCEMENT]. *Quoted service configurations can effectively be monitored and penalized in case of mal- or non-performance.*

It is further assumed that the volume of trade is not restricted. Other than in revenue management in which consumer behavior is anticipated in order to maximize profits subject to limited and perishable resources [310], capacity constraints are not in the focus of the co-opetition mechanism and are deliberately disregarded.

Assumption 5.5 [UNLIMITED SERVICE CAPACITY]. *The volume of trade is unrestricted in the co-opetition mechanism.*

5.2.2 Allocation Function

In this vital step of the mechanism, the auctioneer has to solve the problem of allocating a path $F^* \in F$ that is in line with the desired outcome.[12] Let again $\Delta = \sum_{v_j \in V} \delta_j$ be the monetary surplus that is distributed to the set of service providers via the power ratio. Building upon Section 4.2 (in particular, Equation 4.1), the aggregated surplus $\mathcal{U}^{SP}_{F^*}$ of all service providers owning services in the SVN at hand assembles as the sum of the utility $\mathcal{U}^{SO}_{F^*,o}$ of service offers included in F^* and the utility $\mathcal{U}^{SO}_{F^*,\bar{o}}$ of services that are not a part of F^*.

Definition 5.3 [AGGREGATED SERVICE PROVIDER UTILITY]. *The utility experienced by the set of service providers contributing to the SVN is assembled by the sum of the utility* $\mathcal{U}^{SO}_{F^*,o}$ *attached to allocated service service offers and the sum of the utility* $\mathcal{U}^{SO}_{F^*,\bar{o}}$ *attached to non-allocated service offers. For allocated services,* $\mathcal{U}^{SO}_{F^*,o}$ *is the sum of all price bids and power ratio-based payments net the cost for service provision. Non-allocated services receive*

---

[12] Again, let F^* be defined as a tuple $F^* := (W^*, E(W^*))$.

their power ratio-based share only.

$$\mathcal{U}^{SP}_{F^*} = \mathcal{U}^{SO}_{F^*,o} + \mathcal{U}^{SO}_{F^*,\bar{o}} = \sum_{\substack{v_j \in W^*,\\ e_{ij} \in E(W^*)}} \left(p_{ij} - c_{ij} + \delta_j\right) + \sum_{v_j \notin W^*} \delta_j \tag{5.6}$$

Let $\mathcal{P}_{F^*} = \sum_{e_{ij} \in E(W^*)} p_{ij}$ represent the sum of the price bids submitted by the service providers for the inclusion of their component services into the allocated complex service F^*. If $\mathcal{P}_{F_l}$ was the price of the complex service F_l to be charged from the customer, its utility would evolve as the service configuration-adapted willingness to pay net of the sum of the submitted prices for the edges included in F_l, i.e. $\tilde{\mathcal{U}}^{SC}_{F_l} = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) - \mathcal{P}_{F_l}$. $\tilde{\mathcal{U}}^{SC}_{F_l}$ is called the service customer's interim utility that is created by F_l.

As already argued in Section 4.1, the total payment is collected from the buyer side. That is, it is assumed that the service customer carries the power ratio-based surplus.[13]

Therefore, reserving $\mathcal{P}_{F^*}$ to compensate owners of allocated services for their costs, at the same time keeping budget balance according to Requirement 4.7 in mind, monetary resources that amount to $\tilde{\mathcal{U}}^{SC}_{F^*}$ are available for a power ratio-based distribution Δ.

$$\Delta = \sum_{\substack{v_j \in W^*,\\ e_{ij} \in E(W^*)}} \delta_j + \sum_{v_j \notin W^*} \delta_j = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F^*}\right) - \sum_{e_{ij} \in E(W^*)} p_{ij} \tag{5.7}$$

Therefore, $\tilde{\mathcal{U}}^{SC}_{F_l}$ can be interpreted as the value or utility $\mathcal{U}_{F_l}$ complex service F_l creates in the system, that is, in the customer-specific SVN G.

Definition 5.4 [COMPLEX SERVICE'S UTILITY IN THE SVN]. *The utility $\mathcal{U}_{F_l}$ that a complex service F_l creates in the SVN is the surplus Δ it would account for in case of allocation.*

$$\mathcal{U}_{F_l} = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) - \sum_{e_{ij} \in E(W_l)} p_{ij} \tag{5.8}$$

Given an allocated service F^*, the actual welfare $\mathcal{W}$ in the system is assembled by the sum of the customer utility $\mathcal{U}^{SC}_{F^*}$ and the aggregated service provider utility $\mathcal{U}^{SP}_{F^*}$ with respect to the allocated complex service F^*. Due to the fact that the coopetition mechanism is budget balanced, the platform is neutral in terms of utility since it neither ploughs money into the network nor withdraws any means from

---

[13] From a practical point of view, this is a realistic scenario: the SVN enables the customer to purchase a tailored complex service according to its multiattribute service request. In addition, the SVN offers dramatically reduced lock-ins, variety, and resilience due to the potential multitude of possible complex service instances. For a further discussion, please refer to Section 4.1.

it. Therefore, the utility of the platform operator $\mathcal{U}^{PO}_{F^*}$ leaves the welfare unchanged (and is thus not reflected in $\mathcal{W}$).

$$\mathcal{W} = \underbrace{\alpha \cdot \mathcal{Q}\left(A_{F^*}\right) - \sum_{e_{ij} \in E(W^*)} p_{ij} - \Delta}_{U^{SC}_{F^*}} + \underbrace{\underbrace{\sum_{v_j \in W^*, e_{ij} \in E(W^*)} \left(p_{ij} - c_{ij} + \delta_j\right)}_{U^{SO}_{F^*,o}} + \underbrace{\sum_{v_j \notin W^*} \delta_j}_{U^{SO}_{F^*,\bar{o}}}}_{\mathcal{U}^{SP}_{F^*}} \tag{5.9}$$

From Equation (5.7) and Equation (5.9), we get the following equation:

$$\begin{aligned} \mathcal{W} =& \alpha \cdot \mathcal{Q}\left(A_{F^*}\right) - \sum_{e_{ij} \in E(W^*)} p_{ij} - \Delta + \Delta + \sum_{e_{ij} \in E(W^*)} \left(p_{ij} - c_{ij}\right) \\ =& \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F^*}\right) - \sum_{e_{ij} \in E(W^*)} c_{ij} \end{aligned} \tag{5.10}$$

However, in line with the standard mechanism design assumption, the mechanism operator that collects the service request and service offers does not have access to the allocated service providers' internal costs as this is private information. In order to allocate the path to maximize the expected sum of service customer and provider utility $\tilde{\mathcal{W}} = \bar{E}\left(\mathcal{U}^{SC}_{F^*} + \mathcal{U}^{SP}_{F^*}\right)$, the platform operator must equalize internal costs and bid prices of the service providers, thus setting $\sum_{e_{ij} \in E(W^*)} c_{ij} = \sum_{e_{ij} \in E(W^*)} p_{ij}$.

$$\tilde{\mathcal{W}} = \bar{E}\left(\mathcal{U}^{SC}_{F^*} + \mathcal{U}^{SP}_{F^*}\right) = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F^*}\right) - \sum_{e_{ij} \in E(W^*)} p_{ij} \tag{5.11}$$

Based on Equation (5.11), the allocation function $o : \mathcal{B} \times \Theta \rightarrow F$ can be formulated as a maximization problem that maps service providers' bids and the service customer's type to a feasible and optimal path $F^* \in F$. In order to determine this optimal path, the complex service that maximizes the *expected overall utility of the mechanism participants* shall be chosen. $\tilde{\mathcal{W}}$ equals the expected service provider and service customer utility as well as the platform operator utility. The last two utilities equal zero.

Definition 5.5 [ALLOCATION FUNCTION]. *The allocation function $o : \mathcal{B} \times \Theta \rightarrow F$ maps the service providers' bids and the service customer's request to a feasible complex service $F^* \in F$ that maximizes $\tilde{\mathcal{W}}$:*

$$\begin{aligned} o := \operatorname*{argmax}_{F_l \in F} & \left(\alpha \cdot \mathcal{Q}(\mathcal{A}_{F_l}) - \sum_{i,j:\ e_{ij} \in E(W_l)} p_{ij}\right) \\ s.t. \qquad & \mathcal{U}_{F_l} \geq 0 \ \forall \ F_l \in F \end{aligned} \tag{5.12}$$

If two paths create the same maximum value, one of them is arbitrarily chosen, that is, ties are arbitrarily broken. The constraint $\mathcal{U}_{F_l} \geq 0 \; \forall \; F_l \in F$ is required to guarantee individual rationality of the customer and budget balance at the same time (cp. Definitions 3.11 and 3.10): if $\mathcal{U}_{F_l} < 0 \; \forall \; F_l \in F$ and an allocation was yet to be made, either the customer utility would drop below zero or the platform operator would have to subsidize the transaction.

Example 5.2 [ALLOCATION OF A COMPLEX SERVICE IN THE SVN]. *Let us go back to the exemplary service value network requested by uServ as depicted in Figure 5.1, which consists of the three service offers F_1, F_2, and F_3. uServ's preferences and upper and lower boundaries shall be the same as in Example 5.1. Applying Equations* (5.5) *and* (5.8) *the overall utility provided by each of the three services can be computed.*

$$
\begin{aligned}
\mathcal{U}_{F_1} &= 100 \cdot 0.5 - (10 + 20) = 20, \\
\mathcal{U}_{F_2} &= 100 \cdot 0.58 - (10 + 33) = 15, \\
\mathcal{U}_{F_3} &= 100 \cdot 0.65 - (10 + 30) = 25
\end{aligned}
\tag{5.13}
$$

According to Equation (5.12)*, the mechanism will then allocate $o = F^* = \operatorname{argmax}\{\mathcal{U}_{F_1}, \mathcal{U}_{F_2}, \mathcal{U}_{F_3}\} = F_3$. The underlying overall utility $\mathcal{U}_{F^*} = \mathcal{U}_{F_3} = 25$ of the best path equals the surplus Δ to be distributed via the power ratio (cp. Example 5.5).*

5.2.3 The Power Ratio-based Transfer Function

After defining the allocation function $o(\cdot)$, this section sets the monetary transfers that will be distributed to the involved service providers. The core idea of the payment function $t(\cdot)$ to be applied is both a purely allocation-based component t^1 and a component that takes account of the overall contribution of each service to the specific customer-driven SVN – the *power ratio* t^2. t^1 is directly associated with the chosen complex service in a way that an allocated service v_j receives its successful bid:

$$
t_j^1 := \begin{cases} p_{ij}, & \text{if } e_{ij} \in E(W^*) \\ 0, & \text{otherwise} \end{cases}
\tag{5.14}
$$

The power ratio t^2 is the part which shall implement the bulk of the requirements of the social choice function, capturing and monetizing each service provider's contribution to the overall customer-specific SVN. More precisely, t^2 shall implement the network design goals formulated in Requirements 4.1 to 4.6. As the power ratio is based on solution concepts from cooperative game theory, the concept of coalitions will be used and adapted in order to measure each service's marginal contribution to the SVN. As we are working within the bounds of service value networks, coalitions must must not only be considered as a set of agents, but also and importantly the network structure needs to be incorporated [170]: coalitions are replaced by cooperations (cp. Section 3.2.3).

With respect to a given SVN, $S := \{S_1, \ldots, S_m, \ldots, S_{|\mathcal{P}(V)|}\}$ with $S_m := (V_m, E(V_m))$ denotes the set of all *theoretically possible internal cooperations*.[14]

Definition 5.6 [INTERNAL COOPERATION]. *Given the set of all service offers SO^G that comprise the links that are present in a customer-specific SVN, the set of internal cooperations S is defined by the power set of V and their respective attached links. Each of the $\mathcal{P}(V) = 2^{|V|}$ elements in S consist of a set V_m of services attached with their actual links $E(V_m)$.*

Example 5.3 [INTERNAL COOPERATIONS]. *Again, refer to the SVN G illustrated in Figure 5.1. As $|V| = 4$ services are included in G, 16 internal cooperations are present. These are assembled as follows: $S_1 = \emptyset$, $S_2 = (\{v_1\})$, $S_3 = (\{v_2\})$, $S_4 = (\{v_3\})$, $S_5 = (\{v_4\})$, $S_6 = (\{v_1, v_2\})$, $S_7 = (\{v_1, v_3\}, \{e_{s1}, e_{13}\})$, $S_8 = (\{v_1, v_4\})$, $S_9 = (\{v_2, v_3\}, \{e_{s2}, e_{23}\})$, $S_{10} = (\{v_2, v_4\}, \{e_{s2}, e_{24}\})$, $S_{11} = (\{v_3, v_4\})$, $S_{12} = (\{v_1, v_2, v_3\}, \{e_{s1}, e_{s2}, e_{13}, e_{23}\})$, $S_{13} = (\{v_1, v_2, v_4\}, \{e_{s2}, e_{24}\})$, $S_{14} = (\{v_1, v_3, v_4\}, \{e_{s1}, e_{13}\})$, $S_{15} = (\{v_2, v_3, v_4\}, \{e_{s2}, e_{23}, e_{24}\})$, $S_{16} = \mathcal{G} = (\{v_1, v_2, v_3, v_4\}, \{e_{s1}, e_{s2}, e_{13}, e_{23}, e_{24}\})$.*

Since only cooperations that include complete paths are able to generate value, the set F of complex services shall play a central role when assigning a value to a cooperation. To this end, the concept of characteristic functions from cooperative game theory (cp. Section 3.2.1.4) is, in analogy to Jackson [170], adopted and extended to value functions $\chi : S \rightarrow \mathbb{R}$ that represent costs as well as benefits.

First, it is essential that a cooperation S_m that does not include a feasible path is assigned a value $\chi(S_m) = 0$. Second, as soon as a cooperation yields more than one path, the path providing the highest value is decisive for the calculation of the value function. Thus, the assumption of superadditive value or characteristic functions (as required in the Shapley value and the Myerson value) must be waived in favor of a weaker constraint. $\chi((V_1 \cup V_2, E(V_1) \cup E(V_2))) < \chi(S_1) + \chi(S_2)$, $S_1, S_2 \in S$ is accepted as long as $\chi((V_1 \cup V_2, E(V_1) \cup E(V_2)))$ is not smaller than the most valuable of its components $\chi(S_1)$ or $\chi(S_2)$. Generally spoken, for each $1 \leq x \leq |\mathcal{P}(V)|$, that implies:

$$\chi\left(\left(\bigcup_{m=1}^{x} V_m, \bigcup_{m=1}^{x} E(V_m)\right)\right) \geq \max(\chi(S_1), \ldots, \chi(S_x)) \tag{5.15}$$

Example 5.4 [ADDED VALUE IN INTERNAL COOPERATIONS]. *Consider a random service v_j that is added to a cooperation S_1 with $V_1 \supseteq W_1$, $S_1 \in S$, $F_1 \in F$. Assume that v_j does not account for an additional complex service in $(V_1 \cup \{v_j\}, E(V_1) \cup E(v_j))$. Therefore v_j does not provide any additional value to S_1. On the other hand, if v_j is added to a cooperation S_2 with $V_2 \supseteq W_2$, $S_2 \in S$, $F_2 \in F$, thereby accounting for a cooperation $S_3 = (V_2 \cup \{v_j\}, E(V_2) \cup E(v_j))$ which yields an additional complex service $F_3 \in F$ with $\chi(F_2) < \chi(F_3)$, then $\chi(S_3) = \max\{\chi(F_2), \chi(F_3)\} = \chi(F_3)$.*

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[14] Recall from Section 2.2.3 that $E(V_m) := \{e_{ij} \in E | v_i, v_j \in V_m \cup \{v_s\}\}$. $E(v_j) \subset E(V_m)$ was defined as the set of incoming links that are reasonably associated to a service v_j within V_m.

In line with Definition 5.4, the value function χ of a complex service $F_l \in F$ is set as the service configuration-adapted willingness to pay of the service customer net of the sum of the submitted internal prices for the edges included in F_l:

$$\chi(F_l) := \mathcal{U}_{F_l} = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) - \sum_{e_{ij} \in E(W_l)} p_{ij} \tag{5.16}$$

Thus, the customer service request SR and the service providers' offers SO^G are fully included into the value that is generated by F_l. This gives rise to a third requirement for the value function: if a cooperation S_m yields one or more complex services, however, each of them generates a customer utility less than zero, $\chi(S_m) = 0$ shall hold. Thus, such a cooperation and cooperations which do not yield any path are treated equally by χ.

Based on Equations (5.15) and (5.16), the value function $\chi \in \mathrm{X}$ for any internal cooperation $S_m \in S$ can be precisely defined. X denotes the set of all possible value functions.

Definition 5.7 [Value functions of cooperations in the SVN]. *The value function $\chi : S \rightarrow \mathbb{R}$ maps any $S_m \in S$ to the real numbers, representing the worth of the internal cooperation in terms of how much value or utility this cooperation creates for the system. χ must be defined on $\mathcal{G}$ and any of its subsets $S_m \in S$, requiring $\chi(\emptyset) = 0$, $\chi(S_m) = 0$ if $V_m \not\supseteq W_l \; \forall F_l \in F$, $\chi(S_m) = 0$ if $\mathcal{U}_{F_l} < 0 \; \forall W_l \subseteq V_m, F_l \in F$, and $\chi(S_m) = \max_{W_l \subseteq V_m} \mathcal{U}_{F_l}$ otherwise, as stated in Equation 5.17.*

$$\chi(S_m) := \begin{cases} \max\limits_{W_l \subseteq V_m} \mathcal{U}_{F_l}, & \text{if } \exists W_l \subseteq V_m, F_l \in F, S_m \in S \;\wedge\; \mathcal{U}_{F_l} \geq 0 \\ 0, & \text{if } \nexists W_l \subseteq V_m, F_l \in F, S_m \in S \\ 0, & \text{if } \mathcal{U}_{F_l} < 0 \; \forall W_l \subseteq V_m, F_l \in F, S_m \in S \end{cases} \tag{5.17}$$

In order to determine the power ratio of each of the $|V|$ services in the SVN $\mathcal{G} \in \mathfrak{G}$, a function $\phi : \mathfrak{G} \times \mathrm{X} \rightarrow \mathbb{R}^n$ with $\phi_j(\mathcal{G}, \chi) \in \mathbb{R}$ is defined for each service $v_j \in V$. Each service that generates a positive value, i.e. $\alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) > \mathcal{P}_{F_l}$ holds for at least one complex service the respective service is a part of, is considered vital in at least one instantiation of the customer request.

Incorporating Equation (5.17) and the concept of considering each sub-network $S_m \in S$ of $\mathcal{G}$ into Equation (3.7), or Equation (3.10), respectively, Equation (5.18) yields the *power ratio* of service v_j.

For all internal cooperations $S_m \in S$ a service v_j can (theoretically) be part of, the rightmost term takes a positive value whenever v_j is pivotal to S_m. It measures the service's marginal contribution to the considered internal cooperation. This value is weighted by the probability γ_{S_m} of the underlying cooperation to form consulting the logic introduced by Shapley [292].[15]

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[15] For a detailed interpretation and exemplary calculations of the combinatorics in Equation (5.19), please refer to Section 3.2.1.3.

$$\phi_j(\mathcal{G},\chi) = \sum_{S_m \in S | v_j \in V_m} \gamma_{S_m} \cdot \left(\chi(S_m) - \chi(S_m^{-j})\right) \tag{5.18}$$

with

$$\gamma_{S_m} = \frac{(|V_m| - 1)! \cdot (|V| - |V_m|)!}{|V|!} \tag{5.19}$$

S_m^{-j} denotes the tuple in which v_j and $E(v_j)$ are excluded from S_m. That is, $S_m^{-j} = (V_m \setminus \{v_j\}, E(V_m) \setminus E(v_j))$. Recall from Section 2.2.3 that the set of all reasonable linkages of a service v_j within a cooperation $S_m \in S$ is denoted $E(v_j)$. As soon as a service v_j is included in a cooperation S_m, $E(v_j)$ is also added.

Consequently, each of the services $v_j \in V$ is compensated amounting to their power ratio as the second component of the transfer function:

$$\Phi(\mathcal{G},\chi) := (\phi_1, ..., \phi_n) \tag{5.20}$$

Definition 5.8 [TRANSFER FUNCTION]. *The power ratio-based transfer function (PRTF) for any $v_j \in V$ consists of a directly allocation-dependent component t_j^1 and a component t_j^2 that accounts for the overall network view based on Shapley-style calculus:*

$$t_j = t_j^1 + t_j^2 := \begin{cases} p_{ij} + \phi_j, & \text{if } v_j \in W^*, e_{ij} \in E(W^*) \\ \phi_j, & \text{otherwise} \end{cases} \tag{5.21}$$

Transferred to the service provider level, Equation (5.21) consequently evolves as the sum of all transfers granted to services that are owned by provider $n_h \in N$.

$$T_h := \begin{cases} \sum\limits_{\substack{e_{ij} | e_{ij} \in E(W^*), \\ v_j \in \sigma(n_h)}} p_{ij} + \sum\limits_{e_{ij} | v_j \in \sigma(n_h)} \phi_j, & \text{if } \exists e_{ij} \in E(W^*) \text{ with } v_j \in \sigma(n_h) \\ \sum\limits_{e_{ij} | v_j \in \sigma(n_h)} \phi_j, & \text{otherwise} \end{cases} \tag{5.22}$$

In case of an SVN that offers feasible paths, yet none of them provides a positive utility (i.e. $\chi(S_m) = 0 \ \forall \ S_m \in S$), each of the service providers receives a payment $T_h = 0$. In such a case, we face a trivial game [74].

It is important to note that one basic difference between the Myerson value and the power ratio is the configuration of the value function (cp. Equations 5.15 and 5.17). For the reader's convenience, the path-oriented computation of the value function shown in Equation (5.17) is not defined as a variant of χ, as for instance done in Jackson [170] by introducing monotonic covers of the value function, but is directly included in $\chi \in \mathrm{X}$. This circumstance must be kept in mind when evaluating the co-opetition mechanism in Part III of this thesis: the specialized $\chi \in \mathrm{X}$ as defined in this section differs from the general value function introduced in Section 3.2.1.4.

Example 5.5 [CALCULATION OF TRANSFER FUNCTION]. *Again, reconsider Examples 5.1 and 5.2. Since* $F^* = F_3$*, its involved services* v_2 *and* v_4 *are both compensated amounting to their bid prices in the first place (cp. Equation 5.14). Additionally,* $\Delta = \chi(F_3) = 25$ *is distributed via the power ratio. Equations* (5.18) *and* (5.19) *yield* $\Phi = (3.75, 8.75, 6.25, 6.25)$*. Exemplarily, the computation of* ϕ_4 *is shown in detail. Service* v_4 *can be part of eight internal cooperations (cp. Example 5.3) as listed in the equation below.*

$$\begin{aligned}
\phi_4 = {} & \underbrace{\left[\left(\frac{(1-1)!\cdot(4-1)!}{4!}\right)\cdot(0-0)\right]}_{S_5=(\{v_4\},E(V_5))} + 2\underbrace{\left[\left(\frac{(2-1)!\cdot(4-2)!}{4!}\right)\cdot(0-0)\right]}_{\substack{S_8=(\{v_1,v_4\},E(V_8)),\\ S_{11}=(\{v_3,v_4\},E(V_{11}))}} \\
& + \underbrace{\left[\left(\frac{2}{24}\right)\cdot(25-0)\right]}_{S_{10}=(\{v_2,v_4\},E(V_{10}))} + \underbrace{\left[\left(\frac{(3-1)!\cdot(4-3)!}{4!}\right)\cdot(25-0)\right]}_{S_{13}=(\{v_1,v_2,v_4\},E(V_{13}))} + \underbrace{\left[\left(\frac{2}{24}\right)\cdot(20-20)\right]}_{S_{14}=(\{v_1,v_3,v_4\},E(V_{14}))} \\
& + \underbrace{\left[\left(\frac{2}{24}\right)\cdot(25-15)\right]}_{S_{15}=(\{v_2,v_3,v_4\},E(V_{15}))} + \underbrace{\left[\left(\frac{(4-1)!\cdot(4-4)!}{4!}\right)\cdot(25-20)\right]}_{S_{16}=(\{v_1,v_2,v_3,v_4\},E(V_{16}))=\mathcal{G}} = 6.25
\end{aligned}$$

It is obvious that service v_4 *is pivotal in four of a total of eight internal cooperations it is part of. For instance,* v_4 *is pivotal for* S_{15}*, decreasing its value from* $\chi(S_{15}) = 25$ *to* $\chi(S_{15}^{-4}) = \chi((V_{15} \setminus \{v_4\}, E(V_{15}) \setminus E(v_4))) = 15$*, when "leaving" it, that is, in other words, if* v_4 *was not present. This difference is then weighted by the cooperation's probability to form. The calculation of the other services' power ratios is carried out analogically.*

Altogether, applying Equation (5.21)*, the owners* n_2 *and* n_4 *of the allocated services* v_2 *and* v_4 *receive their price bid and their PRTF, mounting up to* $T_2 = t_2 = 10 + 8.75 = 18.75$ *Euros and* $T_4 = t_4 = 30 + 6.25 = 36.25$ *Euros, respectively. Non-allocated services (and thus, their owners) only receive their PRTF share, i.e. service provider* n_1 *is granted a payment of* $T_1 = t_1 = 3.75$ *Euros and vendor* v_3 *obtains* $T_3 = t_3 = 6.25$ *Euros. Consequently, uServ is charged* $p_{s2} + p_{24} + \chi(F_3) = 65$ *Euros for the requested complex service.*

5.3 Realization

As this work is primarily on networked mechanism design, its focus is not put upon computational issues. Nevertheless, computational complexity can become a problem in terms of the applicability of a mechanism, particularly in settings where the outcome needs to be determined at runtime [245]. To this end, both the allocation and the transfer rule of the co-opetition mechanism are evaluated with respect to their complexity and potential for optimization in Section 5.3.1. In this connection, their algorithmic implementations are illustrated. Section 5.3.2 gives an overview of the agent-based simulation tool which will be utilized in Part III of this thesis.

5.3.1 Outcome Rule: Algorithms & Complexity

As stated in Section 3.1.5, complexity may have diverse sources. The weightiest determinants of the co-opetition mechanism's complexity are the computation of the winning path, that is, the allocation of a complex service (cp. Section 5.3.1.1), and the calculation of payments made to each of the $|V|$ services in the SVN, that is, the transfer function (cp. Section 5.3.1.2).

As a preparation for the following complexity analyses and proposed optimization possibilities, recall the definitions of polynomial and NP-complete mechanisms given in Section 3.1.5 (Definitions 3.15 and 3.16).

5.3.1.1 Allocation Function

This section gives an overview of the allocation algorithm and indicates its complexity. In order to extract the path that maximizes the allocation function (cp. Definition 5.5), the set of all available complex services F, that is, paths within the SVN, need to be found and attached with their value functions $\chi(F_l)$ for all $F_l \in F$. To this end, depth-first search (DFS) [313] is applied. Figure 5.4 illustrates how the concept of DFS is applied to the procedure of extracting the set of all available paths F of an SVN, thereby *(i)* finding the best path F^* and *(ii)* attaching a value function $\chi(F_l)$ to each determined path F_l.

Assume that $|V| = n$ and an equal number of services $|Y^k|$ for all $k \in \{1,\ldots,\tilde{k}\}$ per candidate pool Y^k. For notational simplicity, let $|Y^k| = x$ and $|Y| = y$. In a fully intermeshed SVN, the total number of paths to be extracted evolves as follows:

$$|F| = x^y \tag{5.23}$$

In line with Korf [194] and analogically true for SVNs as the underlying graph, the complexity of DFS is in $\mathcal{O}(x^y)$. Since the space used by DFS grows only as the logarithm of the time required, in practice DFS is time-critical rather than space-critical [194]. Other than purely allocation-based transfer functions, the power ratio requires the value function for each and every path in the SVN. Therefore, the computation of prices and service configurations cannot be cut short in case of unambiguously "dominated" paths as for example possible when the DFS is applied to search for distinct nodes, using procedures such as the Dijkstra algorithm [96].[16]

5.3.1.2 Transfer Function

In order to analyze the PR-based transfer function's complexity, focus is put upon the power ratio, which is obviously the most severe source of complexity within the transfer function. The distribution of t^1 does not yield any additional complexity as its recipients were already determined in the allocation function.

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[16] Note that the Dijkstra algorithm in conjunction with the aggregation of service attributes would yield suboptimal results in case of non-monotonic aggregation types such as *min*, *max*, or *Boolean* operations. Such aggregation cannot be decomposed into sub-problems and optimized partially according to Bellman's Principle of Optimality [33]. However, since cutting dominated (partial) paths is not possible, such optimization methods do not apply in the co-opetition mechanism.

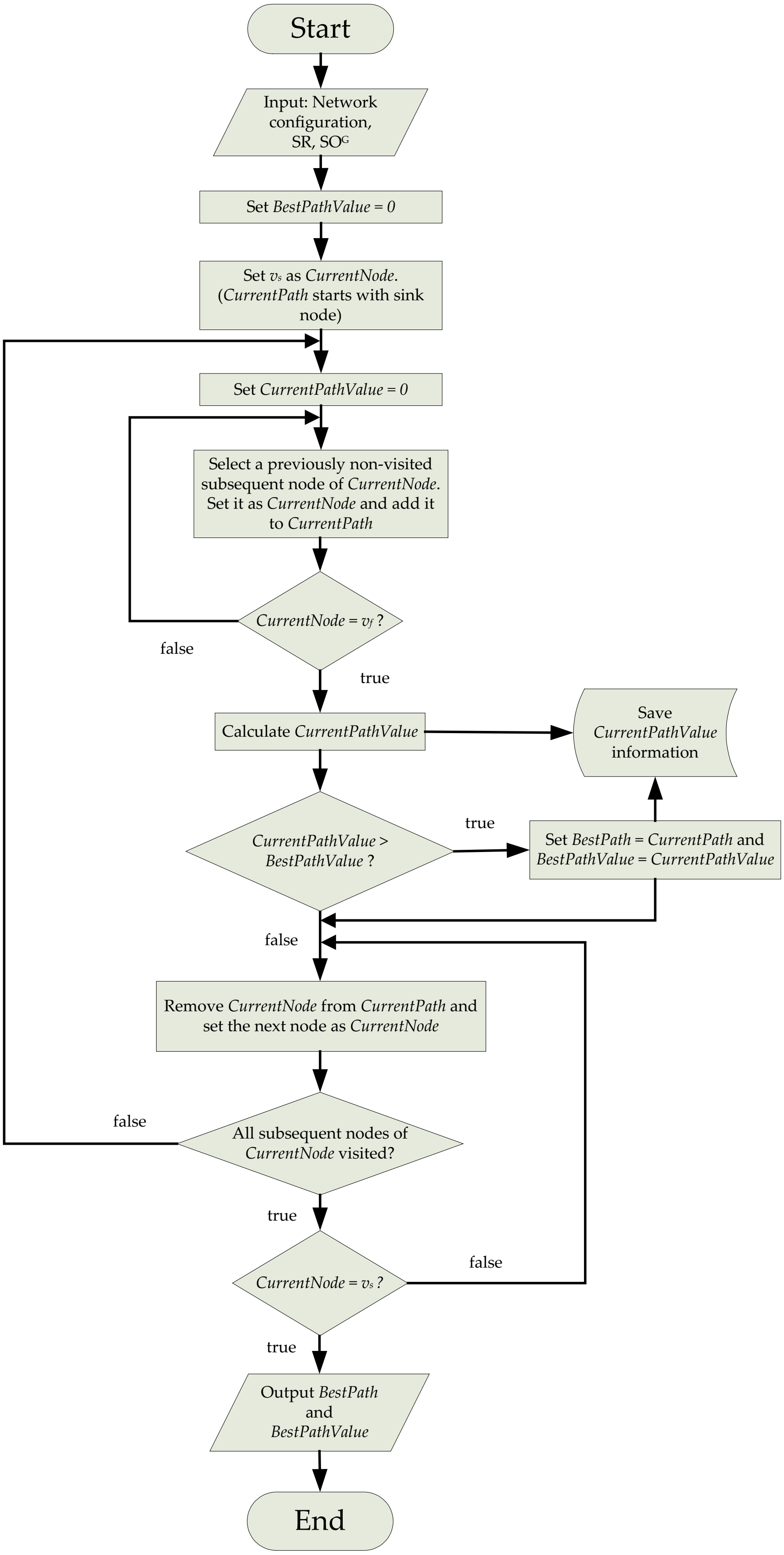

Figure 5.4: Application flow of the co-opetition mechanism's allocation function. The diagram is aligned to the flowchart notation.

Let us at first consider the complexity of the PR calculations in case of naively discovering each possible internal cooperation $S_m \in S$ with $|S| = \mathcal{P}(V)$. Assuming that $|V| = n$, the PR can be computed as follows:

(PR1′) The set of internal cooperations needs to be assembled and valued according to the value function. The complexity of this computation evolves as follows:

$$|S| = \mathcal{P}(V) = 2^n \tag{5.24}$$

(PR2′) Based on (PR1′), the power ratio for each of the n services is computed.

Equation (5.24) shows that, applying the power ratio disregarding the underlying network structure, the identification of cooperations and the allocation of a value function for each of them requires 2^n operations. Since (PR2′) is linear in its input, only requiring n steps, the complexity of the PR computation adds up to $\mathcal{O}(2^n)$. This complexity equals the complexity of the calculation of the Shapley value, originating from finding and valuing all possible coalition that can be formed – without any restrictions in respect of underlying network topologies.

However, when computing the PR, it is possible to harness the structure of service value networks. Only cooperations that include at least one service out of each candidate pool can create a positive value (cp. Figure 5.5). Therefore, in the course of creating the set of internal cooperations, the ones that would be assigned a zero value – that is, those which entirely lack at least one candidate pool's service – can be neglected. The flowchart depicted in Figure 5.6 shows the algorithm of the computation of the PR.

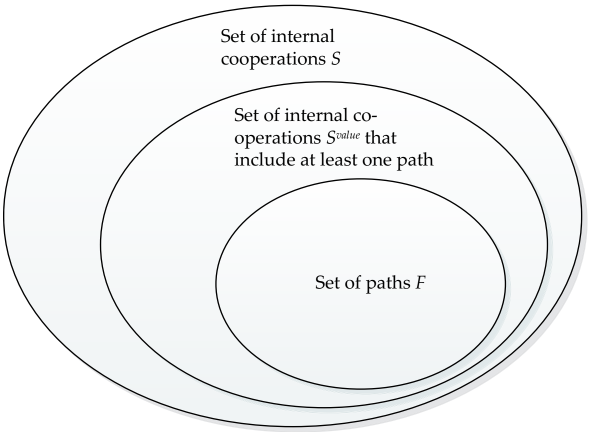

Figure 5.5: Interrelation of the set of internal cooperations, value creating internal cooperations, and paths

Again assume $|Y^k|$ for all $k \in \{1, \ldots, \tilde{k}\}$ per candidate pool Y^k and $|Y^k| = x$, $|Y| = y$. Further assume a worst case scenario with respect to complexity, that is a fully intermeshed SVN (cp. Section 2.2.3). From the allocation function, the set of all $|F| = x^y$ available complex services F and their value functions $\chi(F_l)$ for all $F_l \in F$ are available.

(PR1) According to Equation (5.18), not only paths need to be attached with value functions, but also to the set of cooperations. Therefore, the set of (potentially)

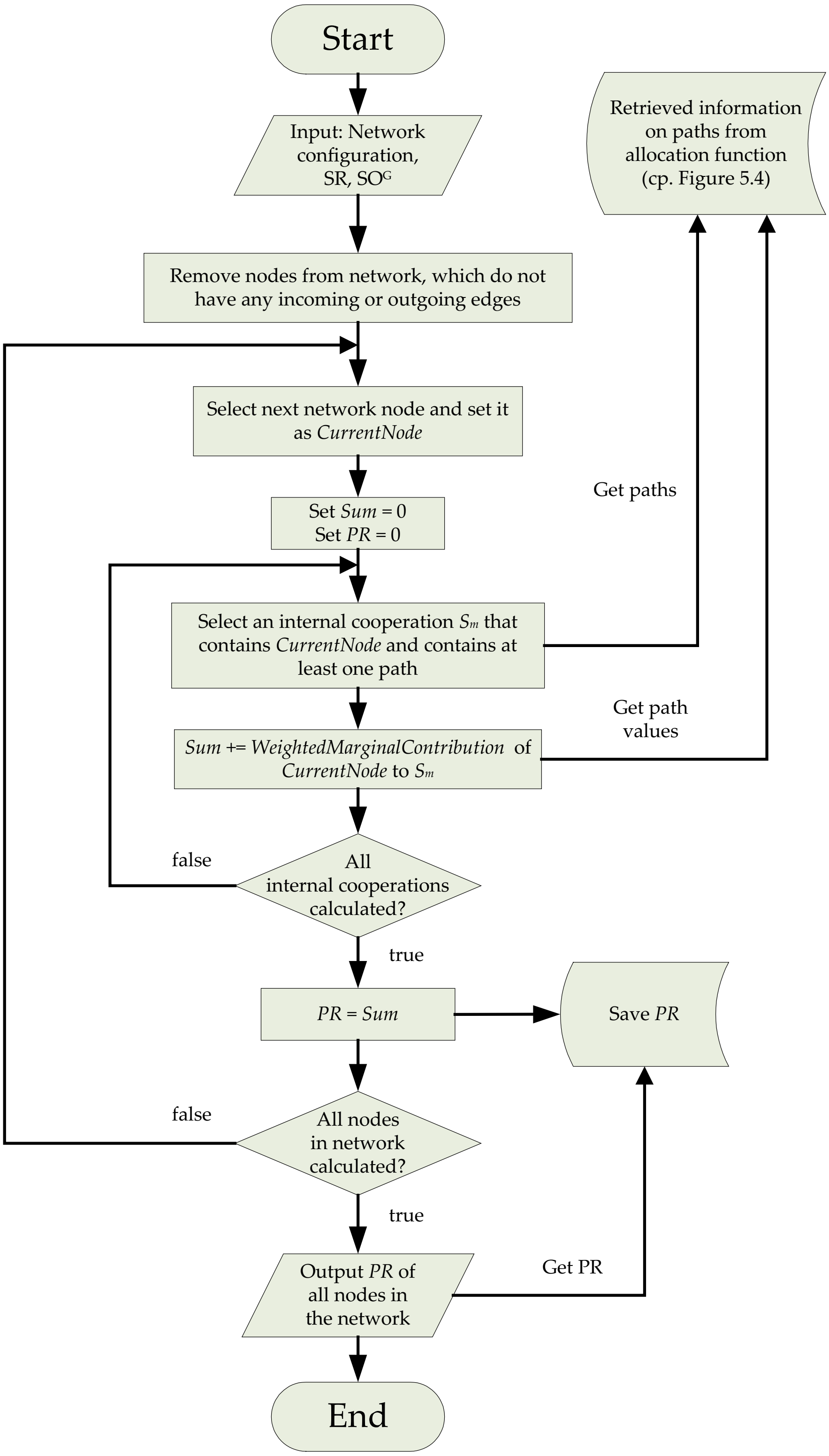

Figure 5.6: Application flow of the power ratio computation. The diagram is aligned to the flowchart notation.

value-creating cooperations $S^{value} \subset S$ needs to be determined, which evolves as follows:[17]

$$|S^{value}| = \left(\sum_{i=1}^{x} \binom{x}{i}\right)^{y} = (2^x - 1)^y \qquad (5.25)$$

The detailed calculation of $|S^{value}|$ can be found in Section A.3. Based on the allocation function, the value functions for the set S^{value} are computed.

(PR2) Based on (PR1), the power ratio for each of the n services is computed.

Thus, the identification of value-creating cooperations in Equation (5.25) is the most severe source of complexity, yielding $\mathcal{O}((2^x - 1)^y)$. For a rising number of services per candidate pool, $\mathcal{O}((2^x - 1)^y) \to \mathcal{O}((2^x)^y) = \mathcal{O}(2^{x \cdot y})$. Since $n = x \cdot y$, the PR is in the same complexity class than the naive calculation of the PR (cp. Equation 5.24): it also exhibits exponential complexity in the number of service offers. Still, by singling out zero-value cooperations at runtime, noticeable differences in the computation of the PR compared to the complexity of Shapley value computations in networks that do not exhibit the SVN characteristics can be observed. The reduction of required operations heavily depends on the parameterizations of x and y. Table 5.2 summarizes the results for different configurations.

Table 5.2: Savings in the number of computations if zero-value cooperations are singled out at runtime compared to the computation of every possible cooperation

Configuration	y=2,x=2	y=2,x=4	y=2,x=6	y=3,x=3	y=4,x=4	y=5,x=5
$\|S\|$	16	256	4096	512	65536	33554432
$\|S^{value}\|$	9	225	3969	343	50625	28629151
Savings	43.8%	12.1%	3.10%	33.0%	22.8%	14.7%

Thus, by singling out zero-value cooperations at runtime, savings concerning the number of cooperations to be determined can be realized, which in turn affects the algorithm's runtime. However, with rising x, the complexity of the algorithm quickly approaches $\mathcal{O}(2^{x \cdot y}) = \mathcal{O}(2^n)$.

5.3.1.3 Implications for the Mechanism Implementation

Merging the complexity of the allocation function $\mathcal{O}(x^y)$ and of the transfer function $\mathcal{O}(2^n)$, the mechanism implementation exhibits exponential complexity and is, therefore, intractable. This result is in line with Deng and Papadimitriou [94] who state that Shapley-style calculations involve all subsets of the considered agents, or services, respectively, and are therefore NP-complete. Simplified variants of the Shapley value, as proposed by Deng and Papadimitriou [94], which only consider

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[17] $\sum_{i=1}^{x} \binom{x}{i}$ sums up the number of different combinations of services within one candidate pool, at least including one service and without considering duplicates and the sequence of services. This is done for all $|Y|$ candidate pools to make sure that at least one service per candidate pool is available in each cooperation.

coalitions of two agents, can be computed in polynomial time, yet are not transferrable to SVN environments.

Applying the Shapley value and its derivates in environments with scarce computational resources, approximation methods come into play. In this connection, two major criteria must be considered: speed and the approximation error [117]. The multilinear extension of the Shapley value provided by Owen [254] turns out to be quite weak in terms of its error. Fatima et al. [117] recently presented a different approximation algorithm based on randomization whose complexity is also linear, yet the approximation error is, on average, lower than in Owen [254]. Both algorithms are designed for voting games, that is, the simplest form of the Shapley value [293]. Such voting games usually include a large number of individuals such that the computation of the exact Shapley value can quickly become infeasible in terms of required computation time [117].

In this thesis, computational issues are cautiously put aside based on the assumption of a quite small number of services per candidate pool in the initial phase of an SVN. Analyzing the variety of service components available at AppExchange approximately five years after it was launched, this assumption seems to be realistic: for instance, by May 2010, AppExchange listed 15 Web services that are concerned with project management, which would be likely to again split into different candidate pools as to their variational functionality.[18]

In such smaller sets of available services, the computational effort of determining the power ratio of all contributing services is within reasonable limits. To conclude with, a runtime analysis is performed that tests the allocation and transfer algorithms in various network configurations, assuming the presence of four service attribute types with different underlying aggregation functions analogue to Table 5.1. On the other hand, a rather undemanding customer is modeled such that preferably every path in the network exhibits a positive value.[19] Moreover, the test is run in a fully intermeshed SVN. Both aspects lead to situation that is close to the worst case assumption. All simulations were run on an Intel Core 2 processor (2.33 GHz) with 2 GB RAM, Windows Vista and Java 1.6. Table 5.3 lists the computation time averaged over 100 runs for allocation and transfer function subject to different network configurations, which are the driver of complexity.

From the results shown in Table 5.3, the exponential complexity of the PR calculation becomes apparent once again – compared to that, the runtime of the allocation function is negligible. In smaller topologies such as $(2,5)$, $(3,3)$, or $(4,3)$ the average computation time of the PR for all services in the network remains within the small digits of seconds. However, in larger topologies, the computation of the PR for all services quickly advances to the time scale of minutes, e.g. 4.8 min in case of $(2,10)$. Therefore, an accurate approximation of the power ratio – and thereby a computational mechanism design approach as introduced in Section 3.1.5 to the co-opetition mechanism is certainly a relevant field of further research (cp. also Section 8.2). In

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[18] `http://sites.force.com/appexchange/results?type=Apps&filter=a0L30000001Qp82EAC&sort=6`, accessed at 05/22/2010.

[19] That is, the customer exhibits a high willingness to pay and low upper and lower boundaries for service quality attributes (cp. Section 5.1.2).

Table 5.3: Runtime analysis of the allocation and transfer function

(y,x)	Runtime Allocation (in msec)	Transfers (in sec)
(2,2)	0.10	0.003
(2,5)	0.44	0.053
(2,10)	1.25	290.3
(3,2)	0.27	0.005
(3,3)	0.48	0.024
(3,5)	1.25	8.235
(3,7)	3.04	1860
(4,3)	0.81	0.455
(4,4)	1.88	30.21
(4,5)	4.04	1449
(5,2)	0.55	0.031
(5,3)	2.12	10.18
(5,4)	21.0	1945
(6,2)	0.62	0.163
(6,3)	5.61	236.0

particular, it will be challenging to achieve tractability and at the same time retain the co-opetition mechanism's desirable properties.

5.3.2 Architecture of the Agent-Based Simulation Tool

To conclude the realization part of this work, the architecture of the agent-based simulation tool is presented. This Java-based program was specifically designed and implemented to evaluate the co-opetition mechanism's properties whenever an analytic approach is not applicable due to a multitude of variable factors. As a remedy, numerical simulations provide a useful means to analyze particular properties of a mechanism through the random generation of multiple problem sets. Especially if agents face large strategy spaces, which dramatically complicates the determination of theoretical solutions, the assignment of agent-based simulations has proven to be a promising approach to solve complex, real-world problems [179, 50**?**].

The class diagram depicted in Figure 5.7 shows the high-level infrastructure of the simulation tool. In general, the architecture can be divided into five components which are again twofold. On the one hand, as a foundation for the agent-based simulation, the Repast 3 toolkit is consulted.[20] Applying Repast, each active component in the evaluated system can be modeled as an agent whose actions can be specified individually in order to simulate their interplay [246]. On the other hand, four components were specifically designed and implemented in order to provide a tailored architecture for the simulation-based analysis of desired properties in service value networks.

The *Repast* component supports the basic functions of the simulation. The class DefaultNode is used to implement a node in a graph, that is, an agent, while DefaultEdge creates relations between them. SimpleModel initializes and coordinates the setup and runs the model. DataRecorder is responsible for the output file of

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[20] `http://repast.sourceforge.net/`

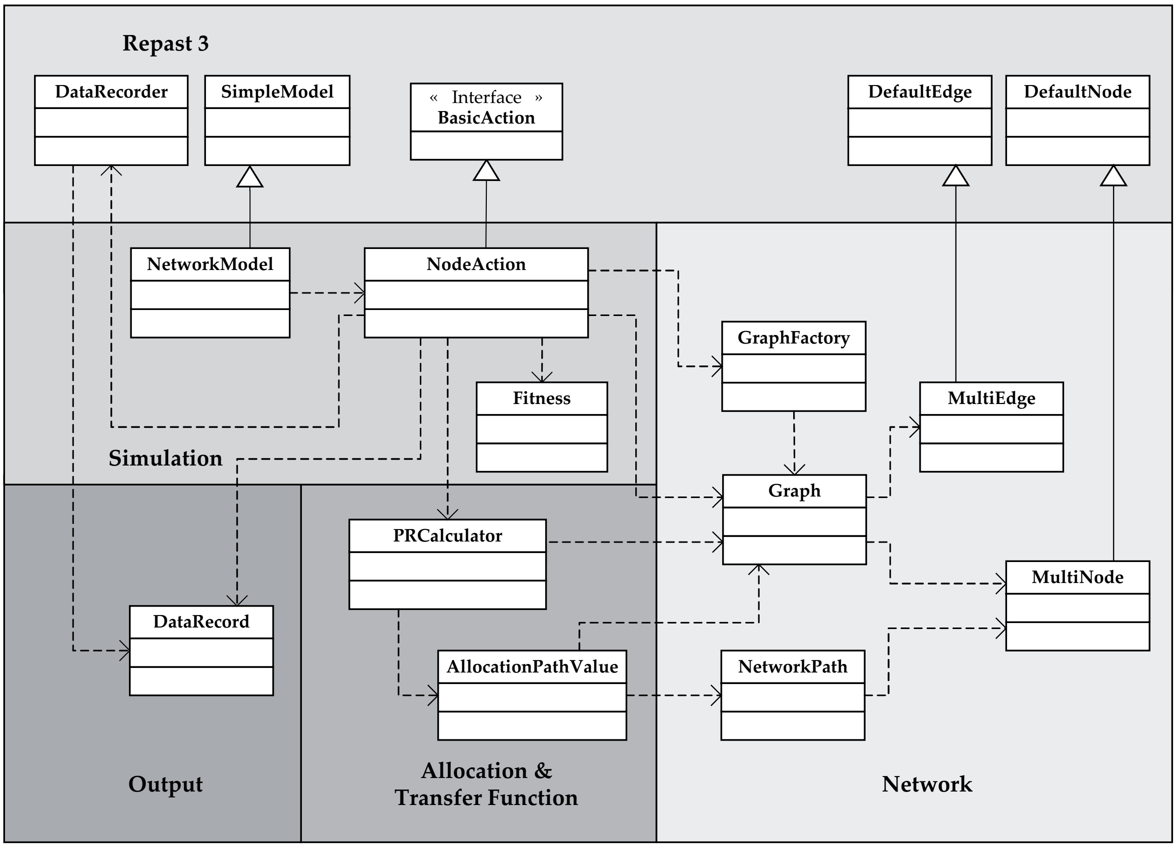

Figure 5.7: Architecture of the agent-based simulation tool

the simulation. BasicAction is the abstract base class for any action of agents to be modeled in the simulation.

The *Simulation* component defines the core of the simulation part of the architecture. In NetworkModel, the settings of the simulation to be conducted are configured. NodeAction includes the concrete action sets that are attached to the agents. In this thesis, such actions are the choice of a distinct market to enter and the bidding strategy of an agent. In this connection, the Fitness class is responsible to handle learning algorithms if applicable. Therein, computerized agents can learn their surroundings and the space of feasible solutions subject to an implemented learning behavior.

The *Network* component of the architecture defines and concretizes the SVN structure. MultiEdge and MultiNode extend the Repast basic classes DefaultEdge and DefaultNode. Here, agents are defined with respect to their service configuration and their costs. The nodes and egdes (that is, the service providers and their linkages) are saved in the Graph class, which must at least contain source v_s and sink v_f. Using the GraphFactory, different SVN network configurations defined by the respective input parameters can be set. For instance, the number of candidate pools and included services, the degree of linkage, or the customer's type is determined here. Finally, NetworkPath saves all relevant information on complete paths, that is, complex services within the initialized SVN.

The actual co-opetition mechanism calculations are done in *Allocation & Transfer Function*. PRCalculator is the main class of the calculator component (cp. Figure 5.6), the calculation of the value of available paths and the determination of the winning complex service is done via depth-first search in the AllocationPathValue class (cp. Figure 5.4).

Finally, the output of the simulation is created in the *Output* component. The class DataRecord defines the output format of the simulation data. Among trivial settings as for instance places after the comma, further consolidation on the data is made within this component if applicable.

The above-introduced agent-based simulation tool is applied in two major evaluation efforts in this thesis. On the one hand, Section 6.4 utilizes an agent-based simulation in order to evaluate the co-opetition mechanism's ability to foster network growth and to set incentives for service providers to join the SVN. On the other hand, the classic mechanism design properties allocative efficiency, incentive compatibility, and individual rationality are analyzed numerically (cp. Chapter 7).

5.4 Summary

Chapter 5 introduced the co-opetition mechanism implementation, thereby representing the central part of this thesis. The concrete allocation and transfer function of the co-opetition mechanism, designed in order to fulfill the requirements imposed in a thorough environmental analysis, addressed the central research question of this work:

Research Question 4 ≺IMPLEMENTATION OF THE CO-OPETITION MECHANISM≻. *How can the co-opetition mechanism be implemented to meet both requirements from network design and from classic mechanism design subject to its ability to handle multiattribute and sequence-sensitive complex services?*

As a solution to Research Question 4, the power ratio was introduced as the key of the co-opetition mechanism, which shall set suitable incentives to enable the realization of the network design goals. The PR embodies the vision of distributing value in commercial service networks by rewarding all potential value creators, not only the "best" ones. Based on the formalization of SVNs, a multiattribute bidding language aligned with recent approaches put forth by procurement auction literature [259, 277], and facilitating an integration of rule-based semantic description techniques [201, 45], the co-opetition mechanism is capable of processing sequence-sensitive composite services and of handling complex QoS aspects.

An analysis of the core algorithms and their complexities found that the co-opetition mechanism is intractable. However, the scope of application and some points of optimization enable an application in SVNs notwithstanding the exponential complexity that is inherent to the transfer function.

Theoretic results that directly follow from the mechanism implementation in terms of the social choice shall be conclusively recapitulated below.

- Requirement 4.2 is directly reflected by the power ratio: service providers are rewarded for standing by with their service offer – even if non-allocated.

Thereby, the availability of incentives for service providers to be continuously prepared for service delivery is secured.

- Moreover, Requirement 4.4 can be confirmed after introducing the co-opetition mechanism: as it is based upon Shapley-style calculus, a clearly defined allocation-based component, and an exact computation of the outcome rule, uniqueness is universally guaranteed.

- By design, the co-opetition mechanism also fulfills budget balance (cp. Requirement 4.7). Generally, a mechanism is budget balanced if allocation and transfer rule can be realized without external subsidies. This is the case in the co-opetition mechanism: the payment made by the service customer is entirely distributed to the set of service providers. The first component of the transfer function assures that allocated service providers receive their price bids p_{ij} while the service customer pays $\sum_{e_{ij} \in E(W^*)} p_{ij}$ (cp. Definition 5.8). Additionally, the power ratio grants $\Delta = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F^*}\right) - \sum_{e_{ij} \in E(W^*)} p_{ij}$ among all services $v_j \in V$. This surplus is also fully distributed by the construction of the PR as will be shown in Section 6.1.1. Since this premium is also borne by the service customer, additional payments to back up the monetary flows between the two market sides are not required.

- Eventually, as already stated above, Requirements 4.9 and 4.10 that are necessary to ensure the applicability of the mechanism in SVNs are also met by the underlying model (cp. Section 2.2) and bidding language (cp. Section 5.1.2).

The remaining properties as stated in Section 4.1.2 will be evaluated in Chapters 6 and 7.

Part III

Evaluation

Chapter 6

Network Design Objectives

This chapter evaluates the network design objectives that take up the largest part of the co-opetition mechanism's social choice (cp. Figure 4.1). The evaluation of network design objectives will both consult formal proofs and numerical simulations. The latter are consulted if analytic approaches are not reasonable due to the transfer function's complexity.

Focussed on the power ratio, Section 6.1 analytically shows that the co-opetition mechanism is *fair* in a game theoretic sense, thereby proving efficiency, symmetry, additivity, and the dummy property (cp. Requirement 4.3). As a direct result from fairness [340], Section 6.2 briefly shows that *cooperational monotonicity* is fulfilled as well (cp. Requirement 4.5). The third analytical proof given in Section 6.3 reveals that the co-opetition mechanism does not only induce a fully intermeshed SVN, which is the highest possible degree of *interconnectedness* (cp. Requirement 4.6), but also retains these linkages as an individually stable result, that is, as a Nash equilibrium.

Recall that above-listed properties are considered given the characteristics of value functions in SVNs as introduced in Section 5.2.3: for each internal cooperation $S_m \in S$, the complex service $F_l \in F$ that maximizes $\mathcal{U}_{F_l}$ accounts for S_m's value function $\chi(S_m) \in \mathrm{X}$. Fairness, cooperational monotonicity, and interconnectedness of services shall be understood subject to value functions out of the set X that comply with this requirement.[1] That is, subject to the application scenario of SVNs, network games $(\mathcal{G}, \chi)$ with $\mathcal{G} \in \mathfrak{G}$ and $\chi \in \mathrm{X}$ will be analyzed.[2]

Finally, Section 6.4 thoroughly studies the co-opetition mechanism's ability to foster *network growth* on service provider side (cp. Requirement 4.1). To this end, an agent-based simulation is set up which shows that the co-opetition mechanism efficiently incentivizes vendors to join the SVN. This evaluation is conducted by comparing the power ratio-based transfer function to an appropriate benchmark that equally distributes the generated value among allocated service providers.

Note that the two remaining network design objectives, namely *readiness to deliver* (cp. Requirement 4.2) and *uniqueness* (cp. Requirement 4.4) are fulfilled by the very construction of the power ratio which was shown in Section 5.4.

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[1] Cp. also Equation (5.15).

[2] Cp. also Definition 3.26.

The proofs and simulations conducted in this chapter consult *(i)* the notation of the SVN formalization introduced in Section 2.2.3 and *(ii)* the bidding language and further notation used for defining the co-opetition mechanism's allocation and transfer function (cp. Sections 5.1 and 5.2).[3]

6.1 Fairness

Requirement 4.3 states that the co-opetition mechanism shall be fair in a game theoretic sense. Due to the application of the power ratio, which was discussed in detail in Sections 4.2 and 5.2.3, a fair distribution of value plays a weighty role: since the rewarded service providers constitute a superset of the allocated ones, transfers are required to be perceived as fair by all participants in order to kiss awake their very willingness to join the SVN.

As discussed in Section 3.2.3.1, cooperative game theory put forth plenty of axioms whose combination results in a fair value distribution. Such a set of properties was proposed by Shapley [292], comprising efficiency, symmetry, additivity, and the dummy axiom (cp. Definitions 3.30 to 3.33), which, taken together, sum up to fairness [340, 149, 74, 289]. The originally postulated forms of the Shapley value and the Myerson value are in fact fair, however the modifications made in this thesis to construct the power ratio require a reassessment of the fairness properties.[4]

Recall from Definition 5.8 that the transfer function t of the co-opetition mechanism is sub-divided into two components: t^1 accounts for compensating the allocated service providers for their costs and is therefore – via the allocation function – only indirectly dependent on the value functions that are assigned to cooperations. It is the power ratio t^2 which accounts for a distribution of monetary means to those service providers that have their offering ready. The worth of this readiness is quantified by the monetized marginal contribution of services to available cooperations. Therefore, value functions are directly referred to, which allows for a restriction of the fairness evaluation to t^2. This restriction will be revisited in Section 6.1.5.

In the current section, the fairness properties as named above will be analytically evaluated.

6.1.1 Efficiency

As introduced in Definition 3.30, efficiency requires the full yield of the game to be distributed [292]. Transferred to service value networks, the value of the game equals $\max\limits_{F_l \in F} \mathcal{U}_{F_l}$ (cp. Definition 5.4). Thus, efficiency can be formulated as follows:

$$\sum_{v_j \in V} \phi_j(\mathcal{G}, \chi) = \max_{F_l \in F} \mathcal{U}_{F_l} \tag{6.1}$$

---

[3] In particular, recall that $S_m = (V_m, E(V_m))$ and $S_m^{-j} = (V_m \setminus \{v_j\}, E(V_m) \setminus E(v_j))$.

[4] Cp. Section 5.2.3, in particular, Definition 5.7.

Theorem 6.1 [Efficiency of the power ratio]. *The power ratio is efficient in any network game* $(\mathcal{G},\chi)$*, that is, the value available in the network is precisely redistributed.*

Proof 6.1. *Considering the cooperation that equals the full SVN* $\mathcal{G}$*, we can directly conclude from Equation* (5.15) *that*

$$\max_{F_l \in F} \mathcal{U}_{F_l} = \chi(\mathcal{G}), \tag{6.2}$$

since $\mathcal{G}$ *must necessarily include the most valuable complex service* $F^* \in F$ *with* $\chi(F^*) = \chi(\mathcal{G})$*. Thus, efficiency can be rewritten as follows:*

$$\sum_{v_j \in V} \phi_j(\mathcal{G},\chi) = \sum_{v_j \in V} \sum_{\substack{S_m \in S| \\ v_j \in V_m}} \gamma_{S_m} \cdot \left(\chi(S_m) - \chi(S_m^{-j})\right) = \chi(\mathcal{G}) \tag{6.3}$$

The power ratio, based on Shapley-style calculus, fulfills such efficiency by construction. This can be nicely shown by consulting a slightly different interpretation of the Shapley-style calculations akin to Examples 3.3 and 3.5: in order to clarify the logic of the Shapley value, scholars oftentimes refer to an intuitive way of its calculation that bases on considering all $|V!|$ *possible permutations* $\Pi = \{\pi_1, \dots, \pi_r, \dots, \pi_{\tilde{r}}\}$ *of* $V = \{v_1, \dots, v_j, \dots, v_n\}$*,* $\tilde{r} = |V|!$*, with the underlying assumption that each of these permutations is equally likely [278, 160]. Thereby,* $f_j(\pi_r)$ *shall denote the marginal contribution that* v_j *yields to* π_r*.*

Table 6.1: Efficiency of the power ratio

	v_1	$\dots$	v_n	V
π_1	$f_1(\pi_1)$	$\dots$	$f_n(\pi_1)$	$\sum_{v_j \in V} f_j(\pi_1) = \chi(\mathcal{G})$
...	$\dots$	$\dots$	$\dots$	$\dots$
$\pi_{\tilde{r}}$	$f_1(\pi_{\tilde{r}})$	$\dots$	$f_n(\pi_{\tilde{r}})$	$\sum_{v_j \in V} f_j(\pi_{\tilde{r}}) = \chi(\mathcal{G})$
Sum	$\sum_{\pi_r \in \Pi} f_1(\pi_r)$	$\dots$	$\sum_{\pi_r \in \Pi} f_n(\pi_r)$	$\tilde{r} \cdot \chi(\mathcal{G})$
$\phi_j(\cdot)$	$\frac{1}{\lvert V\rvert!} \sum_{\pi_r \in \Pi} f_1(\pi_r)$	$\dots$	$\frac{1}{\lvert V\rvert!} \sum_{\pi_r \in \Pi} f_n(\pi_r)$	$\frac{1}{\lvert V\rvert!} \cdot \tilde{r} \cdot \chi(\mathcal{G}) = \chi(\mathcal{G})$

Looking at the rightmost column of Table 6.1, it is obvious from the design of the value function (cp. Equation 6.2) that each of the permutations must be assigned $\chi(\mathcal{G})$ *regardless of the sequence of services within* V*. Akin to the normalization of the sum of single service's marginal contribution by* $|V|! = n! = \tilde{r}$*, the sum of the aggregated services' contributions must also be normalized, which equals the result demanded in Equation* (6.3)*.*

Let us consider this logic analytically: by rearranging Equation (5.19)*, the left-hand side of Equation* (6.3) *can be rewritten as follows:*

$$\phi_j(\cdot) = \frac{1}{|V!|} \sum_{v_j \in V} \sum_{\substack{S_m \in S| \\ v_j \in V_m}} \underbrace{(|V_m|! - 1)! \cdot (|V| - |V_m|)!}_{\gamma^*_{S_m}} \cdot \left(\chi(S_m) - \chi(S_m^{-j})\right) \tag{6.4}$$

$\gamma^*_{S_m} \in \mathbb{N}^+$ denotes the factor that relates internal cooperations to permutations by multiplying marginal contributions S_m that include v_j by their number of occurrence in different permutations $\pi_r \in \Pi$. Since, in this case, the marginal contribution is not indexed via internal cooperations, but via all possible permutations Π as shown in Table 6.1, the value function needs to be updated to a function that is able to process different sequences of V. As introduced above, this function is denoted $f_j(\pi_r)$. Thus, based on Equation (6.4)*,*

$$\phi_j(\cdot) = \frac{1}{|V!|} \sum_{v_j \in V} \sum_{\substack{S_m \in S| \\ v_j \in V_m}} f_j(\pi_r) \tag{6.5}$$

In Equation (6.5)*, the sums can be switched since they are not interrelated.*

$$\phi_j(\cdot) = \frac{1}{|V!|} \sum_{\substack{S_m \in S| \\ v_j \in V_m}} \underbrace{\sum_{v_j \in V} f_j(\pi_r)}_{=\chi(\mathcal{G})} \tag{6.6}$$

By Equation (6.2)*, the marginal contributions of all services equal $\chi(\mathcal{G})$, since the best path is included by any means. Thus, Equation 6.6 can be simplified as shown in Equation* (6.7) *and yields the desired result.*

$$\phi_j(\mathcal{G},\chi) = \frac{1}{|V!|} |V!| \cdot \chi(\mathcal{G}) = \chi(\mathcal{G}) \tag{6.7}$$

□

6.1.2 Symmetry

The symmetry characteristic requires that if two services exhibit perfectly substitutive roles, i.e. contribute the exact same value to each of the cooperations, they need to be granted the same share of the distributed value (cp. Definition 3.31). More formally, two services $v_i \in V$ and $v_j \in V$ are symmetric regarding the network game $(\mathcal{G},\chi)$ if they yield exactly the same marginal contribution to each cooperation:

$$\begin{gathered} \chi((V_m \cup \{v_i\}, E(V_m) \cup E(v_i))) = \chi((V_m \cup \{v_j\}, E(V_m) \cup E(v_j))) \\ \forall\, S_m \in S:\ \{v_i, v_j\} \not\subset V_m,\ \{E(v_i), E(v_j)\} \not\subset E(V_m) \end{gathered} \tag{6.8}$$

In the narrow sense, symmetric services in SVNs *must* thus offer the same functionality, configuration, and prices.[5] As a result, v_i and v_j are required to receive the same payoff. Only looking at the power ratio, it follows that:

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[5] This statement is bound to the requirement that symmetric services yield exactly the same marginal contribution to each internal cooperation. Still, in fully intermeshed SVNs that, for example, include only services that offer the very same price and quality, each and every service technically is symmetric, although not offering the same functionality (cp., for instance, Theorem 6.7).

$$t_i^2 = t_j^2 \Leftrightarrow \phi_i(\cdot) = \phi_j(\cdot) \tag{6.9}$$

Theorem 6.2 [Symmetry of the power ratio]. *The power ratio is symmetric in any network game* $(\mathcal{G},\chi)$*, yielding* $\phi_i(\mathcal{G},\chi) = \phi_j(\mathcal{G},\chi)$ *for any two symmetric services* $v_i \in V$ *and* $v_j \in V$*.*

Proof 6.2. *By symmetry, based on Equation* (6.8)*, the following equation holds:*

$$\begin{aligned} \chi(S_{m_1}^{-i}) =& \chi(S_{m_2}^{-j}) \ \forall\ S_{m_1} \in S : v_i \in V_{m_1},\ E(v_i) \in E(V_{m_1}) \\ & \wedge \forall\ S_{m_2} \in S : v_j \in V_{m_2},\ E(v_j) \in E(V_{m_2}) \end{aligned} \tag{6.10}$$

By Equation (6.8)*,* $|\{S_{m_1} \in S | v_i \in V_{m_1}, E(v_i) \in E(V_{m_1})\}| = |\{S_{m_2} \in S | v_j \in V_{m_2}, E(v_j) \in E(V_{m_2})\}|$*, and thus, each of the elements of the set* $\{S_{m_1} \in S | v_i \in V_{m_1}, E(v_i) \in E(V_{m_1})\}$ *has a corresponding element in* $\{S_{m_2} \in S | v_j \in V_{m_2}, E(v_j) \in E(V_{m_2})\}$ *with* $\gamma_{S_{m_1}} = \gamma_{S_{m_2}}$*. Therefore, Equation* (6.9) *holds as shown in the following:*

$$\begin{aligned} \phi_i(\mathcal{G},\chi) &= \sum_{S_{m_1} \in S | v_i \in V_{m_1}} \gamma_{S_{m_1}} \cdot \Big(\chi(S_{m_1}) - \chi(S_{m_1}^{-i})\Big) \\ &= \sum_{S_{m_2} \in S | v_j \in V_{m_2}} \gamma_{S_{m_2}} \cdot \Big(\chi(S_{m_2}) - \chi(S_{m_2}^{-j})\Big) \\ &= \phi_j(\mathcal{G},\chi) \end{aligned} \tag{6.11}$$

□

6.1.3 Additivity

As introduced in Definition 3.32, additivity considers two different games $(\mathcal{G},\chi)$ and $(\mathcal{G},\chi')$ that involve the same SVN $\mathcal{G}$, but different value functions $\chi \in \mathrm{X}$ and $\chi' \in \mathrm{X}$. Aggregating these two games to a single game $(\mathcal{G},\chi + \chi')$ in which each cooperation $S_m \in S$ is assigned a value function $\chi(S_m) + \chi'(S_m)$ by adding those of the two separate games, services must be granted the same payoffs than in the separate games if the power ratio is additive [296]. For all $v_j \in V$,

$$\phi_j(\mathcal{G},\chi + \chi') = \phi_j(\mathcal{G},\chi) + \phi_j(\mathcal{G},\chi'), \tag{6.12}$$

where the value function of the summed up game is defined by $(\chi + \chi')(S_m) = \chi(S_m) + \chi'(S_m)$ for all $S_m \in S$.

Due to the characteristics of network games and applied value functions therein, additivity is replaced by weak additivity [170].[6]

---

[6] Definition 6.1 is adapted to the SVN formalization.

Definition 6.1 [Weak additivity]. *A solution is weakly additive if the following two equations hold for any monotonic χ and χ', and scalars $q \geq 0$ and $r \geq 0$:*

$$\phi_j(\mathcal{G}, q\chi + r\chi') = q\phi_j(\mathcal{G}, \chi) + r\phi_j(\mathcal{G}, \chi'), \tag{6.13}$$

and

$$\phi_j(\mathcal{G}, q\chi - r\chi') = q\phi_j(\mathcal{G}, \chi) - r\phi_j(\mathcal{G}, \chi') \tag{6.14}$$

Since monotonicity of the value function is a prerequisite for weak additivity (cp. Definition 6.1), the value function applied in the co-opetition mechanism as introduced in Definition 5.7 must be monotonic in order to make statements on the additivity of the power ratio. Jackson [170] defines monotonicity as follows:[7]

Definition 6.2 [Monotonicity of the value function]. *A value function $\chi \in X$ is monotonic if $\chi(S_k) \geq \chi(S_l)$ whenever $V_l \subset V_k$ for all $S_l, S_k \in S$.*

Corollary 6.1 [Monotonicity of the co-opetition mechanism's value function]. *The value function as applied in the co-opetition mechanism is monotonic.*[8]

Proof 6.1. *For all $S_l, S_k \in S$ with $V_l \subset V_k$, monotonicity requires that $\chi(S_k) \geq \chi(S_l)$ (cp. Definition 6.2).*

The value function in the co-opetition mechanism requires that the value of the set union of x cooperations must be greater or equal than the value of the most valuable component therein. That is, for all $S_m \in S$ and $1 \leq x \leq |\mathcal{P}(V)|$,

$$\chi\left(\left(\bigcup_{m=1}^{x} V_m, \bigcup_{m=1}^{x} E(V_m)\right)\right) \geq \max(\chi(S_1), \ldots, \chi(S_x)) \tag{6.15}$$

If $V_l \subset V_k$, it is obvious that S_k can be rewritten as follows:

$$S_k = \underbrace{(V_k \cup \{v_i\}, E(V_k) \cup \{e_{hi}\}) \textit{ with } v_h, v_i \in V_k \textit{ and } e_{hi} \in E(V_k)}_{:=\hat{S}} \tag{6.16}$$

$\hat{S}$ can either be another internal cooperation out of S or an arbitrary combination of services and linkages.[9] *Therefore, by Equation* (6.15),

$$\chi(S_k) \geq \max(\chi(S_l), \chi(\hat{S})) \tag{6.17}$$

---

[7] Definition 6.2 is adapted to the SVN formalization.

[8] The value functions are restricted as explained in the introduction to this chapter.

[9] The links included in $\hat{S}$ must not necessarily be reasonable as specified in Section 2.2.3.

If $\chi(S_l) \geq \chi(\hat{S})$*, Equation* (6.17) *simplifies to*

$$\chi(S_k) \geq \chi(S_l) \tag{6.18}$$

If $\chi(S_l) \leq \chi(\hat{S})$*, Equation* (6.17) *can be rewritten as*

$$\chi(S_k) \geq \chi(\hat{S}) \geq \chi(S_l) \tag{6.19}$$

Equations (6.18) *and* (6.19) *yield the desired result.*

□

Resulting from the monotonicity of the value function applied in the co-opetition mechanism (cp. Corollary 6.1), Theorem 6.3 can be formulated as follows:

Theorem 6.3 [WEAK ADDITIVITY OF THE POWER RATIO]. *The power ratio is weakly additive for any monotonic value function* $\chi \in \mathrm{X}$.

Proof 6.3. *Consider any two monotonic value functions* χ *and* χ' *that follow Equations* (5.15) *and* (5.17) *and any scalars* $q \geq 0$ *and* $r \geq 0$*; then* $q\chi + r\chi'$ *is monotonic. If the power ratio is additive, Equation* (6.13) *holds.* $\phi_j(\mathcal{G}, q\chi + r\chi')$ *can be written as follows:*

$$\begin{aligned}\phi_j(\mathcal{G}, q\chi + r\chi') = \sum_{S_m \in S | v_j \in V_m} & (\gamma_{S_m} \cdot (q\chi(S_m) - q\chi(S_m^{-j})) \\ & + \gamma_{S_m} \cdot (r\chi'(S_m) - r\chi'(S_m^{-j})))\end{aligned} \tag{6.20}$$

Given the monotonicity of the value function[10]*, the right hand side of Equation 6.20 can be reformulated as:*

$$\begin{aligned}&\sum_{\substack{S_m \in S | \\ v_j \in V_m}} (\gamma_{S_m} \cdot q(\chi(S_m) - \chi(S_m^{-j})) + \gamma_{S_m} \cdot r(\chi'(S_m) - \chi'(S_m^{-j}))) \\ &\quad = \sum_{S_m \in S | v_j \in V_m} (\gamma_{S_m} \cdot q(\chi(S_m) - \chi(S_m^{-j}))) \\ &\quad + \sum_{S_m \in S | v_j \in V_m} (\gamma_{S_m} \cdot r(\chi'(S_m) - \chi'(S_m^{-j}))) \\ &\quad = q\phi_j(\mathcal{G}, \chi) + r\phi_j(\mathcal{G}, \chi')\end{aligned} \tag{6.21}$$

By Equations (6.20) *and* (6.21)*, Equation* (6.13) *can be approved.*

---

[10] The value function applied in the co-opetition mechanism is not strictly monotonic (cp. Corollary 6.1 and Equation 6.15), however, weak monotonicity is a sufficient precondition for the power ratio to be weakly additive.

Analogously, assume that $q\chi - r\chi'$ *is monotonic. If the power ratio is additive, Equation* (6.14) *holds. Again, in analogy to Equation* (6.20), $\phi_j(\mathcal{G}, q\chi - r\chi')$ *can be rewritten as:*

$$\begin{aligned}\phi_j(\mathcal{G}, q\chi - r\chi') = \sum_{S_m \in S | v_j \in V_m} & (\gamma_{S_m} \cdot (q\chi(S_m) - q\chi(S_m^{-j})) \\ & -\gamma_{S_m} \cdot (r\chi(S_m) - r\chi(S_m^{-j})))\end{aligned} \tag{6.22}$$

Given the monotonicity of the value function, the right hand side of Equation (6.22) *can be reformulated as:*

$$\begin{aligned}\sum_{S_m \in S | v_j \in V_m} & (\gamma_{S_m} \cdot q(\chi(S_m) - \chi(S_m^{-j})) - \gamma_{S_m} \cdot r(\chi'(S_m) - \chi'(S_m^{-j}))) \\ & = \sum_{S_m \in S | v_j \in V_m} (\gamma_{S_m} \cdot q(\chi(S_m) - \chi((S_m^{-j}))) \\ & - \sum_{S_m \in S | v_j \in V_m} (\gamma_{S_m} \cdot r(\chi'(S_m) - \chi'(S_m^{-j}))) \\ & = q\phi_j(\mathcal{G}, \chi) - r\phi_j(\mathcal{G}, \chi')\end{aligned} \tag{6.23}$$

This is, again, the desired conclusion.

□

6.1.4 Dummy Property

Recall from Definition 3.33 that services which do not add value to any of the present cooperations must receive a zero payment. In other words, if a service's marginal contribution to the overall SVN is always zero, it is worthless with respect to the variety valued by the customer and does not yield an acceptable alternative in case of failure of other services. Therefore, from a fairness perspective, it shall not be granted a share of the power ratio. For all $v_j \in V$,

$$\begin{aligned}\phi_j(\mathcal{G}, \chi) = 0 \text{ if } & \chi((V_m \cup \{v_j\}, E(V_m) \cup E(v_j))) - \chi(S_m) = 0 \\ & \forall S_m \in S : (V_m \setminus \{v_j\}, E(V_m) \setminus E(v_j))\end{aligned} \tag{6.24}$$

Theorem 6.4 [DUMMY PROPERTY OF THE POWER RATIO]. *Services that do not contribute any value to a specific customer-requested SVN must not receive a share of the monetary means that are distributed via the power ratio.*

Proof 6.4. *Theorem 6.4 can easily be shown by considering the value function applied (cp. Equation 5.17) and the logic of the power ratio (cp. Equation 5.18). A service can be part of a "worthless" cooperation* S_m *in two different cases: either if (i) there is no path included in* S_m *or (ii) included paths do not create a positive value* $\mathcal{U}_{F_l}$*:*

$$\chi(S_m) := \begin{cases} 0, & \text{if } \nexists W_l \subseteq V_m, F_l \in F, S_m \in S \\ 0, & \text{if } \mathcal{U}_{F_l} < 0 \end{cases} \tag{6.25}$$

If Equation (6.25) *holds for every cooperation S_m a service v_j is part of, by the monotonicity of the value function (cp. Corollary 6.1), the following implication must hold:*

$$\chi(S_m) = 0 \quad \Rightarrow \quad \chi(S_m^{-j}) = 0 \tag{6.26}$$

For a service $v_j \in V$ that does not contribute any value to any internal cooperation, Equations (6.25) *and* (6.27) *imply that*

$$\phi_j(\mathcal{G},\chi) = \sum_{S_m \in S | v_j \in V_m} \gamma_{S_m} \cdot (\underbrace{\chi(S_m)}_{=0} - \underbrace{\chi(S_m^{-j})}_{=0}) = 0 \tag{6.27}$$

By Equation (6.27)*, it is shown that a service v_j that does not provide any value for the system receives a zero PR payment. This is the desired result as asked for in Equation* (6.24)*.*

□

6.1.5 Summary & Implications

In Section 6.1, the fairness properties of the power ratio were confirmed. With respect to the additivity property, some restrictions to the original additivity axiom consulted by Shapley [292] were necessary: the value function as applied in the PR is not strictly monotonic, however, satisfies monotonicity in its weaker form (cp. Corollary 6.1). Therefore, additivity was relaxed to weak additivity.

As a further result it remains to be noticed that the fairness properties hold for the PR only. While efficiency (cp. Section 6.1.1) and the dummy property (cp. Section 6.1.4) obviously still hold when taking t^1 into consideration, symmetry and additivity do not.

In more detail, symmetry as shown in Section 6.1.2 can only be mapped to the overall transfer function in case of non-allocation of services (since then, $t^1 = 0$). If two symmetric services are situated on the best path, it is obvious that there must be (at least) two paths that maximize the allocation function. As stated in Section 5.2.2, ties are arbitrarily broken in such a case. Thus, if two symmetric services v_i and v_j exist – and maximize the goal function – symmetry in the narrow sense is violated since one service, say v_i, is picked and receives $t_i = t_i^1 + t_i^2$ while v_j only receives t_j^2. If truthful revelation of the services' types is assumed, the profit from t^1 equals zero for both services. Replacing the transfers by the utility as indicator for symmetry, $u_i = u_j$ and thus, symmetry holds again. As will be shown in Section 7.1, the co-opetition mechanism is approximately incentive compatible in several network configurations. Nevertheless, technically, non-truthful bidding disrupts symmetry.

Weak additivity (cp. Section 6.1.3) of the overall transfer function cannot be confirmed due to the different counts of complex service allocations in the separate games $(\mathcal{G},\chi)$ and $(\mathcal{G},\chi')$ compared to the merged game $(\mathcal{G},\chi+\chi')$. In fact, the power ratios of the separate games are additive, however, component t^1 of the transfer function is not. To be more precise, there is one complex service to be allocated in the merged game while in the two separate games one path per game is picked. Thus, a service v_j that is allocated in both games receives $t_j = t^1_j + \phi_j$ in $(\mathcal{G},\chi)$ and $t_j = t^1_j + \phi'_j$ in $(\mathcal{G},\chi')$, while in the merged game, the payoff amounts to $t_j = t^1_j + \phi_j + \phi'_j$. It is obvious that $t^1_j + \phi_j + t^1_j + \phi'_j \neq t^1_j + \phi_j + \phi'_j$. Again, if assuming truthful revelation of the services' types, the there is no profit to be made out of t^1. Replacing transfers by the utility in Equation (**??**), weak additivity holds regardless of the allocation.

In total, the co-opetition mechanism is fair with respect to the power ratio component in the transfer function and subject to the revealed types of the services. Since the PR accounts for remunerating each and every value-creating service, i.e. not only the allocated ones, it is important that fairness holds for this component. Only if the logic of revenue distribution is perceived as evenhanded by the service providers, they will be willing to actually take part in the mechanism. In turn, such acceptance entailing the service providers' very willingness to participate is crucial for the platform operator to get its business up and running. This is, again, a prerequisite for other requirements of the co-opetition mechanism's social choice as stated in Section 4.1.2, for instance, network growth and a high degree of interconnectedness.

Assuming truthful revelation of the services' costs and quality attributes, and replacing transfers by the services' utilities, fairness can be extended to the entire transfer function. Section 7.1 will show that the co-opetition mechanism is approximately incentive compatible for some, but not for every network configuration. Therefore, technically, the co-opetition mechanism as a whole does not fully meet the fairness property. Yet, its manipulation robustness allows for an approximation of fairness with respect to the overall mechanism. This discussion will be picked up in Section 7.1.4 once again.

6.2 Cooperational Monotonicity

In this section, cooperational monotonicity of the power ratio as stated in Requirement 4.5 is evaluated. Recall from Definition 3.34 that cooperational monotonicity shall set particular incentives in terms of competitive service offers. Although value in SVNs is measured on a complex service level, a service's individual contribution shall be incorporated in a way that an increase in its (individual) efficiency must at least lead to an identical or to a larger payoff. An increase of efficiency can either denote a decrease of the internal costs that lowers the bid price or a higher quality offered at a constant price.[11] By cooperational monotonicity, service providers are incentivized to make their offerings more efficient notwithstanding the cooperative aspects of the co-opetition mechanism.

Assume that service $v_j \in V$ has increased its efficiency in the above-mentioned fashion. Further let $\hat{F} \subset F$ denote the set of complex services which include v_j. Definition 3.34 can be mapped to SVNs as stated in the following theorem.

Theorem 6.5 [COOPERATIONAL MONOTONICITY]. *The power ratio is cooperationally monotonic. That is, if an arbitrary service $v_j \in V$ that is part of a certain set of complex services $\hat{F} \subset F$ increases its efficiency in whatever way ceteris paribus, v_j may not be worse off in terms of its power ratio than prior to the increase in efficiency.*

Proof 6.5. *Let $(\mathcal{G},\chi)$ denote the previous game and $(\mathcal{G},\chi')$ the updated game with v_j being more efficient (i.e., offering a lower price or higher quality ceteris paribus). Let further denote $\neg\hat{F} = F \setminus \hat{F}$, that is, the set of complex services that does not include v_j. It directly follows that*

$$\chi'(F_h) = \chi(F_h) \; \forall F_h \in \neg\hat{F} \tag{6.28}$$

and

$$\chi'(F_l) \geq \chi(F_l) \; \forall F_l \in \hat{F} \tag{6.29}$$

By Equations (6.28) *and* (6.29)*, the following coherency can be stated for all $F_h \in \neg\hat{F}$ and $F_l \in \hat{F}$:*

$$\chi'(F_l) - \chi'(F_h) = \chi'(F_l) - \chi(F_h) \geq \chi(F_l) - \chi(F_h) \tag{6.30}$$

By Equation (6.30) *and the computation of the value function for internal cooperations (cp. Equation 5.17), it directly follows that $\phi_j(\mathcal{G},\chi') \geq \phi_j(\mathcal{G},\chi)$, which is the desired conclusion:*

$$\begin{aligned} \phi_j(\mathcal{G},\chi') &= \sum_{S_m \in S | v_j \in V_m} \gamma_{S_m} \cdot \underbrace{(\chi'(S_m) - \underbrace{\chi'(S_m^{-j})}_{=\chi(S_m^{-j})})}_{\geq \chi(S_m) - \chi(S_m^{-j})} \\ &\geq \sum_{S_m \in S | v_j \in V_m} \gamma_{S_m} \cdot (\chi(S_m) - \chi(S_m^{-j})) = \phi_j(\mathcal{G},\chi) \end{aligned} \tag{6.31}$$

□

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[11] In this case, the lower costs are assumed to affect each of the incoming edges of the respective service.

Akin to Theorems 6.2 and 6.3, cooperational monotonicity can only be expressively accepted for the PR, not for the entire transfer function. Replacing the payoff by the utilities and assuming that types are truthfully reported, cooperational monotonicity again holds for the co-opetition mechanism in general.[12]

6.3 Interconnectedness

This section's focus is put upon the co-opetition mechanism's ability to foster interconnectedness of services in an SVN. As introduced in Section 2.2, different approaches to SVNs concerning minimum requirements imposed on the services' interconnectedness, which translates to interoperability in a more technical sense, are likely to be pursued. On the one hand and from a idealistic point of view, such requirements should be as low as possible in order to grant access for a great variety of services to a platform. As postulated in Section 2.2.1, such a lightweight approach is embodied by RESTful Web services that encapsulate functionality and put them behind clearly defined interfaces based on HTTP. However, with respect to valuable, interoperable business applications, composition is not as simple as that. According to Petrie and Bussler [263], asking for such minimal requirements is quite quixotic. Both salesforce.com's AppExchange and current research endeavors such as TEXO rely on open, but proprietary standards in order to enable seamless composition and *compatibility of service modules from a technical point of view* (cp. Section 2.2.5).

Regardless of the approach followed, services need to be implemented according to the imposed requirements – in AppExchange's case enabled by a common implementation via Force.com requiring Apex and Visualforce, the same holds true for TEXO with its unified development environment ISE workbench (cp. Section 2.2.4). That is, interoperability reduces to *strategic considerations* of service providers within the SVN and their decision of how to link their services to other services in the network in order to maximize their own utility.

Turning to strategic considerations, one way to ensure interconnectedness may be that the operator of an SVN "simply" forces each participating service provider to guarantee full interconnectedness of its services to each other service in the network. However, it is quite shortsighted to rely on such a constraint. The co-opetition mechanism shall ascertain a high degree of intermeshing as a result of actions taken by self-interested service providers subject to the SVN's inherent requirement to form cooperations as the very foundation for value creation. In the next section, basic considerations on interconnectedness in SVNs are made, followed by analytical results with respect to the degree of network interconnectedness and stability. Thus, this section refers to economic properties and equilibria of the network in respect of the *service providers' link formation strategies*. The service providers' bidding strategy will be evaluated in Section 7.1.

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[12] Please refer to Section 6.1.5 for an analogous discussion.

6.3.1 Preliminary Considerations

A high degree of interconnectedness is desirable to the platform operator for several reasons. First, it increases the potential of an SVN to satisfy different customers' needs and tastes which provides a multitude of feasible complex service instances to requesters. Such variety is supposed to be valued by customers. In this connection, as a second reason for interconnectedness, customers are expected to prefer purchasing services in adaptive environments in which other providers are raring to go if an allocated service fails to meet a customer's satisfaction for whatever reason. Such dynamic switching is particularly important if critical business applications are offered. Third, a high degree of interconnectedness reduces the probability of single providers becoming too powerful.

To summarize, in connection with the huge potential of the long valley (cp. Section 2.2.1), an increasing choice of services does not only meet requirements that have previously been unheard, but also cultivates new tastes. With respect to the requirement of network growth, a high degree of interconnectedness, and thus, variety, is especially important for SVNs in their early stage of development. It attracts various customers and thus, in turn, leads to a growth of rich candidate pools (cp. Section 6.4).

Recall that in the SVN model, edges $e_{ij} \in E(V)$ in the network $\mathcal{G}$ indicate that services $v_i \in V$ and $v_j \in V$ are linked with each other.[13] As a matter of network design, links in SVNs are formed by individual decision. Owners of services can in fact decide on which other services' outputs to process, yet they cannot keep tabs on which other services use their own outputs. Thus, transferred to network games, we are concerned with the economics of a special case of *one-sided link formation*. With respect to a link e_{ij} between services v_i and v_j, only the service that controls the incoming link (that is, v_j) can decide upon deleting it. Analogously, if there is no connection between v_i and v_j although the customer request would allow for one, it is again only v_j to form it. In other words, the owners of services are to choose with which services from the preceding candidate pool their own services shall be interconnected.

This peculiarity owed to the SVN structure distinguishes the one-sidedness of link formation considered in this work from the classic one-sided link formation in network games as applied by Bala and Goyal [21], Dutta and Jackson [104]. In their models, each agent can unilaterally decide to which other agents it wishes to be linked. Therefore, transferred to the notation above, v_i could decide to establish a link with v_j and vice versa. Yet, this characteristic does not apply to SVNs.

Given the PRTF, it seems favorable for providers to link their services to as many other services as possible. By increasing its intermeshing, a service is located on more paths through the network. Consequently, having more connections, a service is also more often a vital one when it comes to cooperation formation. However, is it possible that services with a powerful standing in the SVN might not want to have a link established to services whose status is unclear – simply in order to strengthen their own position in the SVN? Since the surplus distributed via the services' power

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[13] A detailed discussion on link formation in network games can be found in Sections 3.2.2 and 3.2.3.2. Recall from Section 2.2.3 that $\mathcal{G}$ is defined as a tuple $\mathcal{G} := (V, E(V))$.

ratios is obviously a limited resource, can link formation result in the strengthening of others, in turn leading to a decrease in one's own expected utility?

In the following, it is yet to show if the PRTF sets suitable incentives such that a high degree of interconnectedness is met as a stable and/or efficient equilibrium. Interconnectedness can be measured in the network's density d which denotes the ratio of actual links and all possible edges in the SVN. $\mathcal{G}^{d=1}$ shall denote a fully intermeshed network, subject to the restrictions made on SVNs. For details on the formalization of SVNs and the restrictions made to the set of allowed links, please refer to Section 2.2.3.

6.3.2 Analytic Results

Let $\bar{E}(u_j)$ denote the expected utility of a service v_j in a market that implements the co-opetition mechanism. $prob_j(o)$ shall denote the allocation probability of v_j.

$$\begin{aligned} \bar{E}(u_j) &= prob_j(o) \cdot (p_{ij} - c_{ij} + \phi_j) + (1 - prob_j(o)) \cdot \phi_j \\ &= prob_j(o) \cdot (p_{ij} - c_{ij}) + \phi_j \end{aligned} \tag{6.32}$$

If one prescinds from the service providers' bidding strategies, which are not in the focus here, $(p_{ij} - c_{ij})$ can be set to some value $x \in \mathbb{R}$ and v_j's utility reassembles as follows:

$$\bar{E}(u_j) = \phi_j + prob_j(o) \cdot x \tag{6.33}$$

After a customer request has arrived and has been processed by the platform operator, participating service providers are to decide to which preceding services they want to establish a link (cp. Section 5.1.3 and Figure 5.3). That is, the action space of each service in this preparative step is the set of all possible combinations of links to services of the preceding candidate pool. In other words, we consider a network game in which each service simultaneously selects the list of the other services from the preceding candidate pool to which it wishes to be linked based on its individual expected utility. Individual stability as outlined in Definition 3.36 then corresponds to a pure strategy Nash equilibrium of this game [104]. The formation process defined above is based on Myerson [238]. It is frequently consulted and well-established in network formation approaches [267, 105, 22].[14]

Transferring Definition 3.36 to SVNs, individual stability is the state in which there is no service $v_j \in V$ whose utility can be improved by forming an additional link or by severing an existing link that is at v_j's command. In more detail, for each service $v_j \in Y^k$, $k \in \{1,\dots,\tilde{k}\}$, individual stability includes the set of any possible SVN $D_j(\mathcal{G}) \in \mathfrak{G}$ the respective service v_j can reach based on a given network $\mathcal{G} \in \mathfrak{G}$ by unilaterally choosing a linkage strategy:

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[14] Thus, the network formation process is not dynamic in a sense that it evolves over several decision rounds as, for instance, in Watts [328], Jackson and Watts [174], Goyal and Vega-Redondo [137].

(6.34)

$$D_j(\mathcal{G}) = \underbrace{\{\mathcal{G}' \in \mathfrak{G} | E(V) \setminus \{e_{ij}\} \forall\, v_i \in Y^{k-1}\}}_{D_j^{del}(\mathcal{G})} \cup \underbrace{\{\mathcal{G}' \in \mathfrak{G} | E(V) \cup \{e_{hj}\} \forall\, v_h \in Y^{k-1}\}}_{D_j^{add}(\mathcal{G})}$$

As shown in Equation (6.34), $D_j(\mathcal{G})$ can be decomposed into the networks $D_j^{del}(\mathcal{G})$ that evolve by deleting one or more links from $\mathcal{G}$ and the networks $D_j^{add}(\mathcal{G})$ that form by adding one or more links to $\mathcal{G}$.

Let $\bar{E}(u_j^{\mathcal{G}})$ denote the utility of service v_j subject to network $\mathcal{G}$. Transferring Equation (3.20) to SVNs, a network is individually stable if the following equation holds:

$$\bar{E}(u_j^{\mathcal{G}}) \geq \bar{E}(u_j^{\mathcal{G}'})\ \forall \mathcal{G}' \in D_j(\mathcal{G}) \tag{6.35}$$

Resulting from Equations (6.33) and (6.34), and keeping x constant, Theorem 6.6 is postulated:

Theorem 6.6 [Link formation in SVNs]. *For any constellation of participating services in a customer-specific SVN, the co-opetition mechanism incentivizes every participating service to form every possible link at its command as a Nash equilibrium (i.e., as an individually stable outcome). Considering all services in the SVN, this outcome corresponds to a fully intermeshed SVN.*

Proof 6.6. *In the following it is to show that, based on every possible graph $\mathcal{G} \in \mathfrak{G}$, the fully intermeshed SVN is the only individually stable outcome. Generally, two cases with two sub-cases each need to be considered. First, an arbitrary service $v_j \in Y^k$ deletes a link between v_j and $v_i \in Y^{k-1}$. Second, v_j forms an additional link to some service $v_h \in Y^{k-1}$.*

According to Equation (5.18), *v_j's power ratio assembles as*

$$\phi_j(\mathcal{G},\chi) = \sum_{S_m \in S | v_j \in V_m} \gamma_{S_m} \cdot (\chi(S_m) - \chi(S_m^{-j})) \tag{6.36}$$

Recall that for each internal cooperation $S_m \in S$ (cp. Definition 5.6), the term $(\chi(S_m) - \chi(S_m^{-j}))$ is greater than zero if v_j adds any additional value to S_m.

1. *Now assume that v_j deletes a link e_{ij} from the given network $\mathcal{G}$, resulting in a network $\mathcal{G}' \in \mathfrak{G}$. The number of internal cooperations $|S_m|$ with $v_j \in V_m$ obviously remains unchanged.*
   - (a) *Assuming that some e_{ij} controlled by v_j is part of one or more value-creating complex services, the value of one or more internal cooperations $S_r \in S$ switches from $\chi(S_r) > 0$ to $\chi(S_r) = 0$ since the deletion of e_{ij} inevitably leads to the extinction of at least one path that was available in $\mathcal{G}$. The values $\chi(S_t)$, $S_t \in S$ of internal cooperations that are not affected by the deletion of e_{ij} remain unchanged. The term γ for the cooperations does not change in any way since it*

is only dependent on services, not on their links (cp. Equation 5.19).[15] *Note that* $\{S_m \in S | v_j \in V_m\} = \{S_r \in S | v_j \in V_r\} \cup \{S_t \in S | v_j \in V_t\}$*. Thus, after the deletion, Equation* (6.36) *evolves as follows:*

$$
\begin{aligned}
\phi_j(\mathcal{G}',\chi) = & \underbrace{\sum_{S_r \in S|v_j \in V_r} \gamma_{S_r} \cdot \Big(\chi(S_r) - \chi(S_r^{-j})\Big)}_{=0} \\
& + \underbrace{\sum_{S_t \in S|v_j \in V_t} \gamma_{S_t} \cdot \Big(\chi(S_t) - \chi(S_t^{-j})\Big)}_{<\phi_j(\mathcal{G},\chi) \text{ since } |\{S_t \in S|v_j \in V_t\}| < |\{S_m \in S|v_j \in V_m\}|} \\
& < \phi_j(\mathcal{G},\chi)
\end{aligned}
\tag{6.37}
$$

Since the deletion of a link cannot increase v_j*'s probability of allocation,* v_j*'s utility must decrease. Therefore,* $\bar{E}(u_j^{\mathcal{G}'}) < \bar{E}(u_j^{\mathcal{G}})\ \forall \mathcal{G}' \in D_j^{del}(\mathcal{G})$.

(b) *Now assume that* v_j *does not own any edge* e_{ij} *that creates a value for the system. Then,* $\bar{E}(u_j^{\mathcal{G}}) = 0$ *and does not change through deletion of links. Therefore,* $\bar{E}(u_j^{\mathcal{G}'}) = \bar{E}(u_j^{\mathcal{G}})\ \forall \mathcal{G}' \in D_j^{del}(\mathcal{G})$. v_j *is then indifferent between retaining and deleting controlled links. Taking (1a) and (1b) together, it is a weakly dominant strategy for* v_j *to retain all of its controlled links given a network* $\mathcal{G}$.

2. *Now assume that* v_j *adds a link* e_{ij} *to a given network* $\mathcal{G}$ *resulting in* $\mathcal{G}' \in \mathfrak{G}$*. Again, the number of internal cooperations* $|S_m|$ *with* $v_j \in V_m$ *remains unchanged.*

(a) *Assume that* $v_j \in Y^k$ *can create one or more value-creating complex services by forming a link* e_{hj} *to service* $v_h \in Y^{k-1}$*. Analogue to the argumentation in (1a), one or more internal cooperations* $S_r \in S$ *with* $v_j \in V_r$ *increase their value* $\chi(S_r)$ *induced by the newly emerging valuable paths that were not available in* $\mathcal{G}$*. All other values* $\chi(S_t)$, $S_t \in S$ *of internal cooperations that are not affected by adding* e_{hj} *remain unchanged.* γ *again stays constant. After adding a link, Equation* (6.36) *evolves as follows:*

$$
\begin{aligned}
\phi_j(\mathcal{G}',\chi) = & \underbrace{\sum_{S_r \in S|v_j \in V_r} \gamma_{S_r} \cdot \Big(\chi(S_r) - \chi(S_r^{-j})\Big)}_{>0 \text{ since these cooperations were not available in } \mathcal{G}} \\
& + \underbrace{\sum_{S_t \in S|v_j \in V_t} \gamma_{S_t} \cdot \Big(\chi(S_t) - \chi(S_t^{-j})\Big)}_{=\phi_j(\mathcal{G},\chi)} \\
& > \phi_j(\mathcal{G},\chi)
\end{aligned}
\tag{6.38}
$$

Since the creation of a link cannot decrease v_j*'s probability of allocation,* v_j*'s utility must, in total, increase. Therefore,* $\bar{E}(u_j^{\mathcal{G}'}) > \bar{E}(u_j^{\mathcal{G}})\ \forall \mathcal{G}' \in D_j^{add}(\mathcal{G})$.

---

[15] This is also true if the deletion of e_{ij} "isolates" v_i, that is, after deletion, v_i does not have any outgoing link. Technically, isolated services can remain in the SVN without changing the distributed power ratios.

(b) *By the same argumentation than in (1b), services that cannot add any value creating paths are indifferent between doing nothing and adding new links. Taking (2a) and (2b) together, it is thus a weakly dominant strategy for v_j to add possible links to a given network $\mathcal{G}$.*

Taking the result of (2), it is obvious that the fully intermeshed SVN $\mathcal{G}^{d=1}$ evolves as a result of the services' (weakly) dominant strategy to add any possible link to a given network. Once the fully intermeshed SVN is reached, according to (1), none of the services wants to delete a link. Therefore, $\mathcal{G}^{d=1}$ is (weakly) individually stable:

$$\bar{E}(u_j^{\mathcal{G}^{d=1}}) \geq \bar{E}(u_j^{\mathcal{G}'}) \; \forall \mathcal{G}' \in D_j(\mathcal{G}^{d=1}). \tag{6.39}$$

□

It follows directly from Proof 6.6 that it is a *strictly dominant strategy* for all value-creating service providers to establish each link that is at their command, since agents as described in (1b) and (2b) do not add any value to the system.

$$\forall\, v_j \in V \text{ with } \exists\, V_m \ni v_j \wedge \chi(S_m) > 0 : \; \bar{E}(u_j^{\mathcal{G}^{d=1}}) > \bar{E}(u_j^{\mathcal{G}'}) \; \forall \mathcal{G}' \in D_j(\mathcal{G}^{d=1}) \tag{6.40}$$

Note that the service providers are not equipped with full information about the other services types – one of the basic assumptions in mechanism design is the private information character of preferences. Rather, service providers are likely to have some prior about the other agents' type distribution. However, theoretically assessing the link formation scenario, it is always a dominant strategy for service providers to opt for the formation of each possible link. Assuming that a service provider offers one service $v_j \in V$, this strategy is strictly dominant as long as the service provider's prior about the other services' types results in an expected positive power ratio ($\bar{E}(\phi_j) > 0$). This is a quite reasonable assumption.

Notwithstanding the fact that the choice of link formation strategies is a simultaneous process in reality, Example 6.1 provides an illustration of Theorem 6.6 that is structured step-by-step to show that adding links is beneficial to all services. Moreover, as above-stated, service providers do not have full information about the other services' offerings as implicitly assumed in Example 6.1. Exact utilities are consulted to show that forming every link at a service's command is in fact the "best answer" to any possible link formation strategy played by the other services.

Example 6.1 [LINK FORMATION AND DELETION: IMPACT ON SERVICES' UTILITIES]. *Assume that the SVN $\mathcal{G} = \{\{v_1, v_2, v_3, v_4\}, \{e_{s1}, e_{s2}, e_{14}, e_{23}\}\}$ represents the "starting point" for network formation (cp. Figure 6.1).*[16] *Further assume that each service is owned by a different service provider. Without loss of generality, let the types of services be merely determined by prices.*

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[16] In reality, the starting point is always the (degenerated) SVN which does not include any link. The example at hand is consulted to exemplify the development of the services' utilities in different networks.

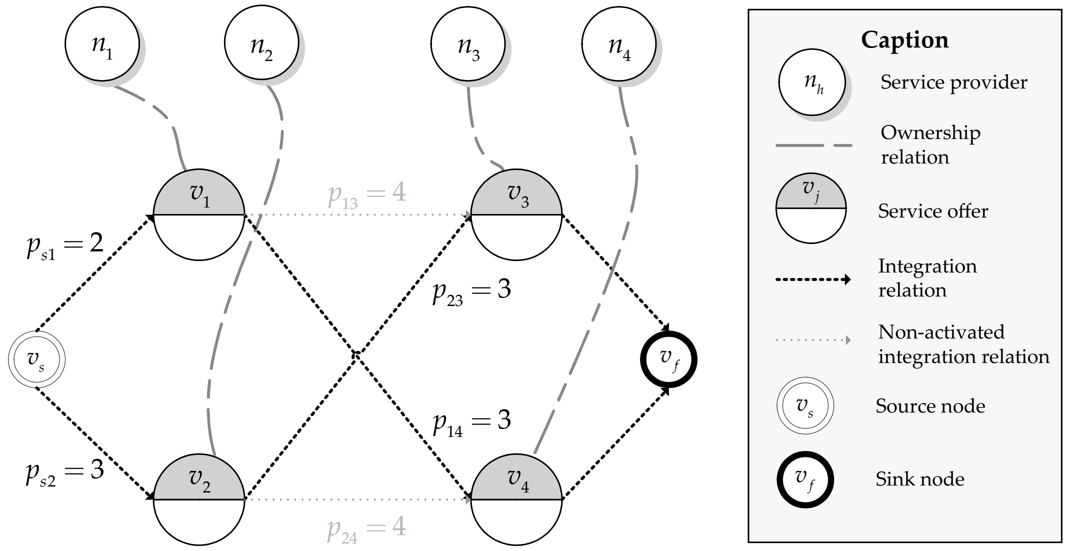

Figure 6.1: Link formation: A simple example

Assume that the customer's willingness to pay is $\alpha = 8$. *Again keeping* $p_{ij} - c_{ij} = x_j$ *constant (cp. Equation 6.33),* $\mathcal{G}$ *yields the utilities* $u_1 = 1 + x_1$, $u_2 = u_3 = 0.5$, *and* $u_4 = 1 + x_4$.

While v_1 *and* v_2 *cannot add any link*[17], v_3 *can form* e_{13} *and* v_4 *may add* e_{24}. *Assume that* $p_{13} = p_{24} = 4$. *The decision of link formation can be formulated as a strategic-form game. In total,* v_3 *can choose from four actions: "delete* e_{23}*", "do nothing", "add* e_{13}*", and "delete* e_{23}*, add* e_{13}*".* v_4*'s action set is assembled analogously: "delete* e_{14}*", "do nothing", "add* e_{24}*", and "delete* e_{14}*, add* e_{24}*". The utilities of* v_3 *and* v_4 *are shown in the matrix depicted in Figure 6.2 for each of the possible actions.*

			v_4		
		add e_{24}	no action	delete e_{14}	add e_{24}, delete e_{14}
v_3	add e_{13}	$\frac{7}{12}, \frac{11}{12} + x_4$	$\frac{2}{3}, \frac{5}{6} + x_4$	$\frac{4}{3} + x_3, 0$	$1 + x_3, \frac{1}{6}$
	no action	$\frac{5}{12}, \frac{13}{12} + x_4$	$\frac{1}{2}, 1 + x_4$	$1 + x_3, 0$	$\frac{2}{3} + x_3, \frac{1}{6}$
	delete e_{23}	$0, \frac{5}{3} + x_4$	$0, \frac{3}{2} + x_4$	$0, 0$	$0, \frac{1}{2} + x_4$
	add e_{13}, delete e_{23}	$\frac{1}{3}, 1 + x_4$	$\frac{1}{3}, \frac{5}{6} + x_4$	$1 + x_3, 0$	$\frac{3}{4} + x_3, \frac{1}{4}$

Figure 6.2: Link formation: Actions and resulting utilities as a strategic-form game

The game exhibits a unanimous pure-strategy Nash equilibrium: it is for both services to add the missing link e_{13} *and* e_{24}*, respectively. Note that for* v_3*, given any other action of* v_4*, adding* e_{13} *is always the best response. Likewise,* v_4 *always wants to add* e_{24} *regardless*

---

[17] We do not consider v_1's and v_2's possibilities to delete their links since this action would isolate the services and inevitably turn their expected payoffs to zero.

of v_3's action. Thus, both agents hold a dominant strategy regardless of the other agents' actions.

The resulting fully intermeshed SVN $\mathcal{G}^{d=1}$ is individually stable – none of the services can improve its expected utility by unilaterally deviating from $\mathcal{G}^{d=1}$ (that is, by deleting a link).

6.3.3 Summary & Implications

The result of this section is highly favorable for two reasons. First, Requirement 4.6 which demands a preferably high degree of interconnectedness of participating services in a specific SVN is perfectly met. Regardless of the actual bidding strategies of the participating service providers concerning their prices and attributes, the co-opetition mechanism ensures that every service provider's link formation strategy is to add every possible link. Second, as the fully intermeshed network is individually stable, that is, a Nash equilibrium, this result is guaranteed to be sustainable. None of the participating service providers has an incentive to unilaterally delete links from the fully intermeshed SVN since it does not increase its expected utility.

Taking these results together, the SVN is guaranteed to provide the maximum variety of complex services to the customer. Assuming an equal count of services $|Y^k|$ in each of the $|Y|$ candidate pools, the co-opetition mechanism assures an offering of $|Y^k|^{|Y|}$ complex services – this is the number of paths through a fully intermeshed SVN. In practice, this means that more different instances of the complex service demanded can be offered, possibly ranging from cheap, low-quality to high-priced premium quality services, thereby offering complex services for a multitude of customer types. In particular, an SVN applying the co-opetition mechanism is guaranteed to yield the most suitable complex service for a customer given the available component services since link formation is not distorted by strategic considerations. In the face of the most striking feature of SVNs, namely the power of combinatorics induced by the long valley of Web services, the co-opetition mechanism assures an optimal exploitation of their potential. Economides [106] puts it in a way that cuts to the core: it is compatibility that makes complementarity actual.

From a more global point of view, the co-opetition mechanism is designed to meet the characteristics of an environment in which competition and cooperation are present at the same time. This is strikingly made clear by the result of this section. From an arbitrary service's perspective, services in the same candidate pool are competitors since they directly compete for being allocated. Services in all of the other candidate pools are complements and inevitable partners in terms of satisfying a specific customer request. Applying the co-opetition mechanism, for service providers it is always preferable to form every possible link to complementary services (that is, to the services in the preceding candidate pool). It is an important result that the co-opetition mechanism is able to fully support the co-opetitive nature of SVNs and thereby fosters the postulated power of combinatorics in the long valley (cp. Section 2.2).

Other than in purely competitive transfer functions, the formation of each possible link turns into a strictly dominant strategy for all services that potentially (expect to)[18] create value for the system (cp. Equation 6.40). Coupled with the co-opetition mechanism's ability to retain competitiveness and offer payments to non-allocated services at the same time (cp. Section 6.2), the explicit incentives for link formation are quite unique. As Blau [45] showed in a simulation-based approach for his complex service auction with interoperability transfer function extension (ITF)[19] subject to similar assumptions, first and foremost, neglected investment costs for link formation, interoperability expressed in the network density settles down to approximately 67.6%. The ITF is particularly designed to foster interconnectedness. A transfer function proposed by Parkes et al. [260] that equally distributes additional value to allocated service providers (cp. also Section 6.4.1) reaches a degree of interconnectedness of 66.7% on average [45]. As a striking result, the degree of interconnectedness of allocated service offerings amounts to 77.1% when applying the ITF and to 75.7% in case of resorting to the above-named benchmark. For non-allocated services, this number is considerably smaller (65.3% vs. 64.4%). The co-opetition mechanism yields a fully intermeshed SVN as a result of the services' equilibrium link formation strategies, that is, a degree of interconnectedness of 100%, no matter if a service is allocated or not.

This result would certainly change in absolute terms if introducing investment costs for link formation. However, due to the requirements imposed by the platform (cp. e.g. the ISE workbench in the TEXO Service Management Platform), additional investment costs reflecting the degree of similarity of the interfaces of the services to be connected are unlikely to occur. Services interfaces within the SVN should ideally be compatible to other services in the candidate pool, that is, work seamlessly with other service components. Yet, if investment costs are to be considered, they will both occur for SVNs applying the co-opetition mechanism and for any tested benchmark in the same proportion. Thus, starting from a fully intermeshed SVN, the co-opetition mechanism is still likely to account for a higher degree of interconnectedness than, for instance, above-listed benchmarks whose degree of interconnectedness is clearly lower than 100%, even if investment costs for link formation equal zero.

6.4 Network Growth

In this section the co-opetition mechanism's ability to incentivize service providers to join the service value network as postulated in Requirement 4.1 is analyzed. It is essential to attract participants in order to establish a running business in the launch phase of an SVN. Only if a platform operator succeeds in establishing a large enough base of participants, that is, a critical mass, network effects can kick in and bring about positive network effects [188].[20]

Network growth is nearly impossible to measure in absolute terms: network growth is not a desiderata in terms of classic mechanism design. It would be quite

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[18] As stated in Section 6.3.2, this is a quite reasonable assumption for each service that takes part in a call for participation and call for bids (cp. Section 5.1.3).

[19] Please refer to Section 4.3 for a more detailed discussion.

[20] For a more detailed introduction into network growth as a design goal in networks, please refer to Sections 3.2.3.2 and 4.1.2.

blurry to specify some absolute number of desired services on the platform as a target figure to be reached within a given time frame. Likewise, taking some targeted market share as an output size is unrealistic – potential competitors can hardly be classified in terms of their portfolio.

For instance, as shown in Section 2.2.4.2, the number of registered services at salesforce.com's AppExchange platform increased from virtually zero in 2005 to around 900 in May 2010. However, taking these numbers as a benchmark does not suit the problem at hand. The environment of AppExchange with salesforce.com's already existent and successful core service Salesforce CRM created a huge potential for network effects since the customers as one side of the market have already been in place. Moreover, through the inherent link to the "main service" Salesforce CRM, later renamed into Sales Cloud 2, the example AppExchange is generally "biased" with respect to the variety offered. For the concept of SVNs that underlies this thesis, such restrictions are not made. In total, the growth property needs to be evaluated in relative terms which requires the consultation of a suitable benchmark as introduced in the next section. Section 6.4.2 will prepare the simulative main part of the evaluation (cp. Section 6.4.3) by pointing out some analytic considerations.

6.4.1 Benchmark: The Equal Transfer Function for Allocated Services

In order to benchmark the results yielded by the co-opetition mechanism with respect to properties that cannot be evaluated analytically, a comparison to other mechanisms or transfer functions, respectively, is required. Importantly, to retain comparability, the focus is put upon a payment rule that distributes the same amount of money to service providers. That is, both price bids of allocated services and an additional surplus $\Delta = \mathcal{U}_{F_l}$ shall be distributed (cp. Sections 5.2.2 and 5.2.3). Moreover, the allocation function introduced in Definition 5.5 is adopted to the benchmark as it stands. That is, the benchmark introduced in the following includes the same allocation rule $o(\cdot)$ as the co-opetition mechanism, however, differs in how transfers are distributed.

Compared to the PRTF, a "conservative" payment scheme shall be consulted that *(i)* does not distribute payments to non-allocated service providers and *(ii)* does not set particular incentives besides the ones for allocation. To this end, the payment rule $t^{E1}(\cdot)$ is consulted that distributes Δ equally among all *allocated* services analogue to the *Equal Rule* utilized by Parkes et al. [260].

Definition 6.3 [EQUAL TRANSFER FUNCTION FOR ALLOCATED SERVICES (ETF-1)]. *The ETF-1 distributes the system's surplus Δ in equal shares to each allocated service v_j with $e_{ij} \in E(W^*)$:*

$$t_j^{E1} = \begin{cases} p_{ij} + \frac{1}{|Y|}\Delta, & \text{if } v_j \in W^*, e_{ij} \in E(W^*) \\ 0, & \text{otherwise} \end{cases} \tag{6.41}$$

The ETF-1 represents a "neutral" payment scheme compared to the PRTF as it equally distributes the same surplus, however, does not implement particular incentives besides its inherently included competitive element [260]: other than using the PRTF, the ETF-1 exclusively rewards allocated service providers. That is, the ETF-1 can certainly be interpreted as a more competitive payment scheme than the PRTF.

Therefore, as a suitable benchmark to evaluate the growth incentives implemented by a market using the PRTF (denoted as $m^{PRTF} = (o, t^{PR})$), a market $m^{ETF-1} = (o, t^{E1})$ is consulted which implements the ETF-1.[21]

6.4.2 Analytical Considerations

In order to show that the PRTF incentivizes participants to join the SVN, and therefore, creates the basis to initiate network effects and positive feedback loops, a comparison of expected payoffs for service providers when deciding upon entering m^{PRTF} or m^{ETF-1} is required. In the remainder of this section it is assumed that each service provider n_h owns exactly one service v_j, that is, $\sigma(n_h) = \{v_j\}$ and $\bar{\sigma}(v_j) = n_h$.[22] Both mechanisms allow for an expected utility greater or equal zero for any service provider given truthful revelation of their types. Thus, subject to their preferences, service providers expect to be never worse off compared to non-participation. In this evaluation, v_j's decision solely depends on the utility $\bar{E}(u_j^m)$ it expects to gain in each market m. Let ζ_j denote the percentage of the surplus Δ that is distributed to vendor v_j according to the PR. This percentage is independent from the actual allocation.[23] The probability $prob_j(o)$ indicates the probability of service v_j being allocated, while $(1 - prob_j)(o)$ denotes the probability of the respective service being not allocated.

$$\bar{E}(u_j^{PRTF}) = prob_j(o) \cdot \left(p_{ij} + \zeta_j\Delta - c_{ij}\right) + (1 - prob_j(o)) \cdot \left(\zeta_j\Delta\right) \tag{6.42}$$

$$\bar{E}(u_j^{ETF-1}) = prob_j(o) \cdot \left(p_{ij} + \frac{1}{|Y|}\Delta - c_{ij}\right) + (1 - prob_j(o)) \cdot 0 \tag{6.43}$$

In the following, it is assumed that costs c_{ij} equal the bid price p_{ij}. For a detailed analysis of service providers' bidding strategies, please refer to Section 7.1. A major result of this analysis is that the co-opetition mechanism does not allow for major deviation from truth-telling in the tested scenarios which depict realistic SVNs in their launch phase (cp. Section 7.1.4). Therefore, the simplifying assumption of holding bid prices constant at the services' true types is acceptable for the analysis

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[21] For the reader's convenience, *mechanism* and *market* will be used interchangeably. Generally, the term *market* embraces a lot more than just the mechanism [240]. For the analysis in Section 6.4, a differentiation is not required since service providers base their decision solely upon the utility that is generated by the allocation and transfer function, that is, the mechanism.

[22] Therefore, the terms *service* and *service provider* can be used interchangeably.

[23] In order to analyze specific parts of the transfer function, its illustration slightly differs from the notation consulted in Section 6.3.2. Here, ϕ_j is replaced by a relative consideration $\zeta_j \cdot \Delta$.

of network growth capabilities. That way, bidding strategies are not variable such that this section's evaluation can be concentrated on the markets' attractiveness to potential vendors.

Further assume that an arbitrary service provider v_j can choose which market to enter without additional investment or switching costs. That is, each service $v_j \in V$ can choose from two actions $z_j = \{m^{PRTF}, m^{ETF-1}\}$ out of its strategy space Z_j. This strategy space is identical for each service. Including the simplification made in terms of the price bid, v_j realizes a utility which can be simplified to $\zeta_j \cdot \Delta$ in case of $z_j = m^{PRTF}$. Accordingly, choosing m^{ETF-1}, its payment amounts to $\frac{1}{|Y|} \cdot \Delta$ if allocated while v_j leaves empty-handed if not being allocated (cp. Figure 6.3).

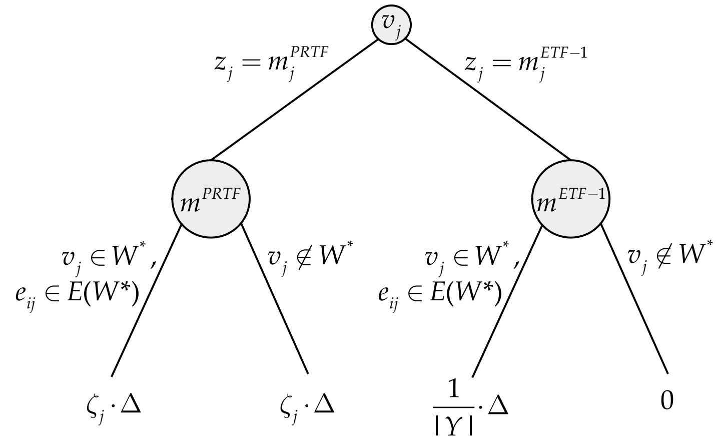

Figure 6.3: Market choice: Action space of an arbitrary service provider

An analytical comparison of PRTF and ETF-1 is not trivial: due to the complexity of the power ratio computation[24] and the multitude of included parameters, formal proofs are only reasonable to a limited extent including a large number of restrictions as exemplarily shown in the following theorem.

Theorem 6.7 [EQUAL EXPECTED UTILITY IN BOTH MARKETS]. *Assuming a fully intermeshed network*[25] *which features exactly $|Y^k|$ service providers in each candidate pool and identical prices and qualities (i.e. $p_{ij} = \mu$, $\mathcal{A}_j = \eta \ \forall \ v_j \in V$), the expected utility for an arbitrary service provider v_j in m^{PRTF} equals the expected payoff in m^{ETF-1}, that is $\bar{E}(u_j^{PRTF}) = \bar{E}(u_j^{ETF-1})$.*

Proof 6.7. *Since all services in the SVN are alike, their allocation probabilities are directly connected with the number of service providers $|Y^k|$ present in each candidate pool Y^k as outlined in Equation* (6.44)*:*

$$prob_j(o) = \frac{1}{|Y^k|} \tag{6.44}$$

Hence, the probability of not being allocated assembles as follows:

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[24] The calculation of the set of internal cooperations as required in Equation (5.18) yields exponential complexity as shown in Section 5.3.1.2.

[25] Links are only permitted between adjoining clusters according to the rules stated before (cp. Section 2.2.3).

$$prob_j(\bar{o}) = 1 - prob_j(o) = \frac{|Y^k| - 1}{|Y^k|} \tag{6.45}$$

Taking Equations (6.44) *and* (6.45) *as a basis, the expected utility in* m^{PRTF} *can be calculated. The power ratio is identical for all present services since they take over symmetric roles in the SVN (cp. Section 6.1.2).*

$$\bar{E}(u_j^{PRTF}) = \frac{1}{|Y^k|} \cdot \frac{1}{n}\Delta + \frac{|Y^k| - 1}{|Y^k|} \cdot \frac{1}{n}\Delta = \frac{1}{n}\Delta \tag{6.46}$$

According to Equation (6.41)*, the ETF-1 leads to the following expected payoff:*

$$\bar{E}(u_j^{ETF-1}) = \underbrace{\frac{1}{|Y^k|} \cdot \frac{1}{|Y|}}_{|Y^k| \cdot |Y| = n} \Delta = \frac{1}{n}\Delta \tag{6.47}$$

□

But how do the payoffs evolve in case of different prices or quality attributes? Consider two simple variations of the assumptions made in Theorem 6.7:

1. Let service provider v_j bid a price $p_{ij} = \mu + \varepsilon$, $\varepsilon > 0$, with all other services ceteris paribus. That is, v_j creates less utility than any other service in the SVN. Thus, $prob_j(o) = 0$. Nevertheless, in the PR-based market, v_j is pivotal to certain cooperations as long as paths including v_j yield a positive utility. Based on Equations (6.42) and (6.43), this service is granted the following expected payoffs in m^{ETF-1} and m^{PRTF}:

   $$\bar{E}(u_j^{ETF-1}) = 0 < \bar{E}(u_j^{PRTF}) = (1 - prob_j)(o) \cdot \zeta_j \Delta \tag{6.48}$$

2. On the other hand, consider a situation in which a service v_j offers a price bid of $p_{ij} = \mu - \varepsilon$, $\varepsilon > 0$ ceteris paribus. In this case, $prob_j(o) = 1$ since v_j creates a utility that is higher than the utility created by any other service. This leads to

   $$\bar{E}(u_j^{ETF-1}) = 1 \cdot \frac{1}{|Y|}\Delta \tag{6.49}$$

   and

   $$\bar{E}(u_j^{PRTF}) = 1 \cdot (\zeta_j \cdot \Delta) \tag{6.50}$$

   According to the service's contribution to the network, i.e. in this case, dependent on ε, $\zeta_j \in [\frac{1}{n}, 1)$ can be either greater or less than $\frac{1}{|Y|}$, such that a comparison of $\bar{E}(u_j^{ETF-1})$ and $\bar{E}(u_j^{PRTF})$ is not possible by implication.

Considerations for changes in the bid quality attributes can be made analogously to Equations (6.48) to (6.50).

In general, it is clear that applying the PRTF must lead to a decreasing utility of (at least) some allocated service providers compared to the ETF-1 since Δ is redistributed from merely allocated services to all services that are potentially valuable for the system. In the remainder of Section 6.4 this issue will be picked and it will be evaluate how utilities of different types of service providers evolve in both of the considered markets.

6.4.3 Simulation-Based Approach

Generally, the analytic considerations made in the previous section still include various restrictive assumptions such as, for instance, a fully intermeshed network and (nearly) identical prices and quality attributes. A relaxation of these assumptions leads to a multitude of dependencies within the analytical considerations which do not allow for formal proofs within reason. Therefore, a numerical approach to study the effects of a PR-based transfer function is presented. That way, more general results shall be created that also allow for strategic recommendations. In particular, *different types of service providers* and their strategies with respect to choosing a market are the focal point of the following evaluation.

Thus, the objective of this section is to numerically compare an SVN that implements the PRTF to an ETF-1-based service market. The basic claim is that the design of the co-opetition mechanism, in particular the application of the PRTF, fosters the attraction of more service providers to an SVN than a market implementing a transfer function based on a purely competition-oriented distribution of payoffs. Such a recurring payment granted in the initial phase of the SVN, even if the offered service is not regularly allocated, may not only lower the entry barrier for potential service providers by partly compensating their sunk investments, but also countervail the risk of uncertain revenues in the newly entered environments. In the following evaluation, the effect of the PRTF with respect to services that have already been designed for the SVN at hand is considered, thereby assuming a decision of service providers to either enter m^{PRTF} or m^{ETF-1} with both markets relying on the same minimal requirements.

Therefore, the hypothesis to be tested in this section is derived as follows:

Hypothesis 6.1 [Network growth]. *The co-opetition mechanism that implements power ratio-based transfers attracts a greater number of service providers than a mechanism that applies the equal transfer function for allocated service providers ceteris paribus.*

6.4.3.1 Simulation Model & Settings

The following simulation model, its settings, and its results underly the assumption that different types of service providers, that is, service providers offering different levels of QoS and different prices, appear in a *uniformly distributed fashion* when bidding for the inclusion into a customer request. The problem is approached in an agent-based simulation, modeled as an n-person game. Purpose of the numerical approach is to relax the restrictions made in the analytic considerations. That way, previously fixed parameters such as the network configuration, cost structures of service providers, their service configurations, and customer types can be varied.

As indicated in Section 6.4.2, the network topology $(|Y|, |Y^k|)$ is of crucial importance when analyzing the co-opetition mechanism's ability to incentivize network growth. Through the topology, the number of candidate pools $|Y|$ and the number of services per candidate pool $|Y^k|$ is expressed. By $|Y^k|$, the competition to be included in the allocation is determined. $n = |Y| \cdot |Y^k|$ denotes the total of services included in the SVN and therefore indicates the level of overall competition for a share in Δ.

In the simulation, complex services including $|Y| = 2$, $|Y| = 3$, $|Y| = 4$, and $|Y| = 5$ candidate pools are considered. It is argued that $2 \leq |Y| \leq 5$ depicts the average service mashup in terms of features functionalities. Analyzing business-related mashups listed at ProgrammbleWeb.org, the average of included service components in the category CRM amount, for instance, to 2.6[26]. Finance mashups include on average 2.3 services per mashup.[27] Without loss of generality, an identical count of services $|Y^k|$ per candidate pool Y^k is assumed. As the fully intermeshed SVN evolves as a stable state from service providers' link formation strategies (cp. Section 6.3.2), the network's density is set to $d = 1.0$ for all network topologies.

Out of the above-listed parameters, selected network configurations shown in Table 6.2 will be examined. In the evaluation of the simulation results, focus is primarily put upon on network configurations that feature a smaller number of services per candidate pool as the are assumed to be realistic in the launch phase of an SVN. However, in order to get an indication on how results change with rising $|Y^k|$, the configurations (2,8), (2,10), (3,5), and (3,6) are additionally tested (cp. Section B.1).

Table 6.2: Network growth: Tested network configurations

$\|Y\| = 2$	$\|Y\| = 3$	$\|Y\| = 4$	$\|Y\| = 5$
(2,2)	(3,3)	(4,2)	(5,3)
(2,5)	(3,4)	(4,3)	
(2,8)	(3,5)	(4,4)	
(2,10)	(3,6)		

In respect of the service providers' types, prices p_{ij} are randomly drawn from $U(0;1.0]$. For simplicity and without loss of generality, it is assumed that the configuration only consists of one service attribute that is denoted as "service quality" (sq). Therefore, $\mathcal{A}_j = \{a_j^{sq}\}$. On a complex service level, sq is aggregated via the average operator, that is, $\mathcal{A}_{F_l} = \frac{1}{|Y|} \cdot \sum_{v_j \in W_l} a_j^{sq}$. The values for sq are also drawn uniformly, i.e. $a_j^{sq} \in U(0;1.0]$.

Not only on provider-side, but also on customer-side, different types are randomly drawn. In more detail, the customer type assembles from two arguments.

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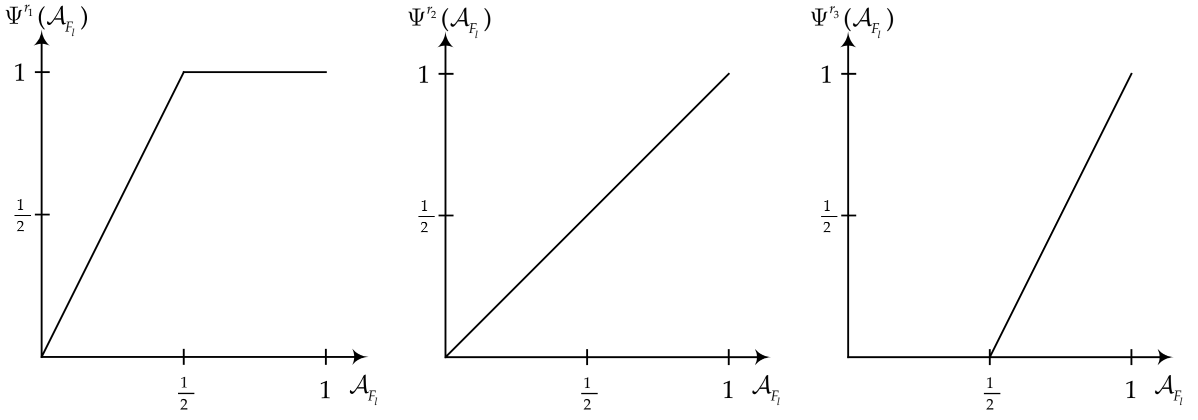
[26] `http://www.programmableweb.com/tag/crm`, accessed on 2010/05/24.

[27] `http://www.programmableweb.com/tag/finance`, accessed on 2010/05/24.

First, the customer's preferences for the service quality which are formalized by its upper and lower boundaries $\Gamma = \left(\gamma_B^{sq}, \gamma_T^{sq}\right)$ and second, its willingness to pay α. Three different preferences for sq are considered, denoted by $R = \{r_1 = low, r_2 = medium, r_3 = high\}$. These preferences translate into Γ as follows: $\Gamma^{r_1} = (0, \frac{1}{2})$, $\Gamma^{r_2} = (0,1)$, and $\Gamma^{r_3} = (\frac{1}{2},1)$. A linear coherency $\Psi^r(\mathcal{A}_{F_l})$ between upper and lower boundary is assumed that allows for the computation of the customer's idiosyncratic valuation for each offered complex service $F_l \in F$ as depicted in Figure 6.4.



(a) Valuation for Γ^{low} **(b)** Valuation for Γ^{medium} **(c)** Valuation for Γ^{high}

Figure 6.4: Different customer types' valuation for service quality

Thus, a complex service offering F_l which exhibits $\mathcal{A}_{F_l} = \frac{2}{3}$ is valued $\Psi^{r_1}(\mathcal{A}_{F_l}) = 1$, $\Psi^{r_2}(\mathcal{A}_{F_l}) = \frac{2}{3}$, and $\Psi^{r_3}(\mathcal{A}_{F_l}) = \frac{1}{2}$, respectively, by the different customer types. $r_1 = low$ represents a rather undemanding customer whereas $r_3 = high$ represents a customer demanding premium services. $r_2 = medium$ is obviously situated right in the middle of r_1 and r_3 and shall thus model a customer with an average preference for service quality. It is argued that the tested customer types represent a cross section of customers that realistically approach the SVN.

Additionally, the customer's willingness to pay α is randomly drawn from $U(0; 2.0 \cdot |Y|)$. α is stated relative to the number of candidate pools in order to retain comparability between different network configurations. For instance, a customer with $\alpha = 0.5 \cdot |Y|$ is willing to pay the mean price of a (perfectly fitting) complex service. This is a quite low (i.e. competitive) willingness to pay. $\alpha = 1 \cdot |Y|$ denotes a willingness to pay of the maximum price that can be set in the SVN, however, valid for a complex service with a service fit of 1. By the argument of equal price and cost, $\alpha = 1$ can be interpreted a quite reasonable value (which is also the expected value of α). On the other hand, $\alpha = 2$ denotes a customer with a quite high willingness to pay, however, again, only for a perfectly fitting service. α and Γ put together assembles the customer's type in the underlying simulation model. Table 6.3 summarizes the simulation settings for the network growth simulation.

In sum, for each network configuration, the simulation includes $SR = 20{,}000$ rounds. In each round, prices and service qualities as well as the customer's type are drawn randomly as pointed out above. Then, in each round, an arbitrary service provider v_j is chosen. This service provider is classified in one of the nine classes $\{\varrho_1, ..., \varrho_9\}$ according to its service quality and its price as depicted in Table 6.4.

Table 6.3: Network growth: Simulation settings

Parameter	Value
Network	
Tested network configurations $(\|Y\|,\|Y^k\|)$	(2,2), (2,5), (3,2), (3,3), (3,4), (4,3), (4,4), (5,3). In Section B.1: (2,8), (2,10), (3,5), (3,6)
Network density	$d = 1.0$
Service providers	
Prices of services	$p_{ij} \in U(0;1]$
Service configuration	$a_j^{sq} \in U(0;1]$
Service customers	
Lower and upper boundaries for service quality	$\Gamma^{low} = (0,\frac{1}{2})$, $\Gamma^{medium} = (0,1)$, $\Gamma^{high} = (\frac{1}{2},1)$
Willingness to pay	$\alpha \in U[0;2 \cdot \|Y\|]$

Table 6.4: Network growth: Classification of service provider types

Price bid / Service quality	$q_j \in (0;\frac{1}{3}]$	$q_j \in (\frac{1}{3};\frac{2}{3}]$	$q_j \in (\frac{2}{3};1]$
$p_{ij} \in (0;\frac{1}{3}]$	$\varrho_1 = (low,low)$	$\varrho_2 = (low,med)$	$\varrho_3 = (low,high)$
$p_{ij} \in (\frac{1}{3};\frac{2}{3}]$	$\varrho_4 = (med,low)$	$\varrho_5 = (med,med)$	$\varrho_6 = (med,high)$
$p_{ij} \in (\frac{2}{3};1]$	$\varrho_7 = (high,low)$	$\varrho_8 = (high,med)$	$\varrho_9 = (high,high)$

After classifying the arbitrarily chosen service provider according to Table 6.4, its (hypothetical) utilities for both markets u_j^{PRTF} and u_j^{ETF-1} are calculated as shown in Figure 6.3 in each of the 20,000 simulation rounds.[28] Figure 6.5 depicts the stepwise procedure of the simulation.

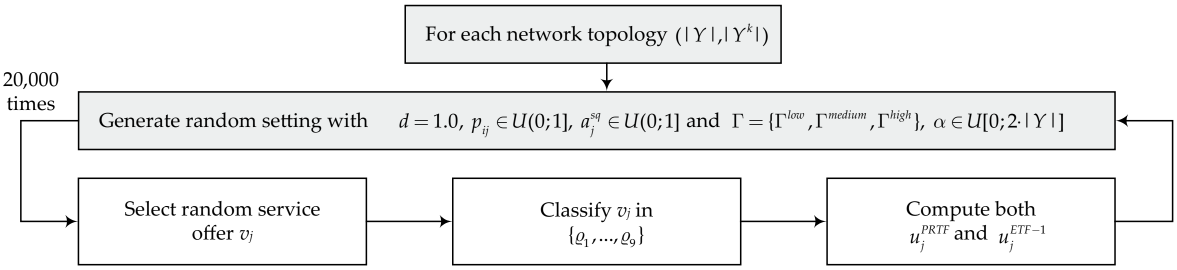


Figure 6.5: Market choice: Simulation model

Note that SVNs underlie quickly changing preferences and types of participants. Thus, it is assumed that each auction setting is different from the preceding one which makes learning from past situations impossible and each game can therefore be treated as a *one-shot game*. That is, the simulation of multiple rounds relying on partially unchanged parameters is done for statistical reasons, not in order to be as close as to reflecting reality. Due to the large number of transactions, interdependencies are likely to be canceled out sufficiently [268, 285, 56].

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[28] In order to grasp a sufficiently large amount of simulation data for each service provider class subject to other varied parameters, a quite high number of simulation rounds is required. A sensitivity analysis was performed for selected configurations which tested both 10,000 simulation rounds and 30,000 as well as 50,000 simulation rounds. All of these simulations' results did not significantly differ from the results of the simulation that consults 20,000 rounds.

6.4.3.2 Simulation Results

As above-stated, it is assumed that services out of each of the nine classes $\{\varrho_1, \dots, \varrho_9\}$ are uniformly distibuted. Therefore, Hypothesis 6.1 translates into nine sub-hypotheses stating that m^{PRTF} attracts a greater number of service providers than m^{ETF} for each of the agent classes. Technically, Hypothesis 6.1 can be reformulated as follows:

Hypothesis 6.2 [AVERAGE SHARE OF SERVICE PROVIDER CLASSES OPTING FOR m^{PRTF} AND m^{ETF-1}]. *For each of the service provider classes ϱ_h, the share of service providers opting for the PRTF-based market is higher than the share of service providers opting for m^{ETF-1}.*

Hypothesis 6.2 can be measured via a comparison of the utilities u_j^{PRTF} and u_j^{ETF-1} of the arbitrarily chosen service provider v_j in each round. v_j chooses m^{PRTF} if $u_j^{PRTF} > u_j^{ETF-1}$ and vice versa. In case of $u_j^{PRTF} = u_j^{ETF-1}$, none of the markets is chosen. The number of market choices can then be summed up and set into relation with the total number of rounds played within each provider class. However, the mere count of choices can be misleading since absolute utility values are not accounted for. If, for instance, one market is chosen in nine out of ten rounds based on a marginal difference, however, the other market is preferred once based on a considerably larger utility, market one is quite clearly preferred in 90% of the cases, yet in terms of utility, the result would most probably be not significant. Therefore, Hypothesis 6.1 is alternatively restated as follows:

Hypothesis 6.3 [UTILITY OF SERVICE PROVIDER CLASSES IN m^{PRTF} AND m^{ETF-1}]. *For each of the service provider classes ϱ_h, the utility of service providers in the PRTF-based market is higher than the utility of service providers in the market which implements the ETF-1.*

Analogously to the approach sketched above, u_j^{PRTF} and u_j^{ETF-1} are compared in each simulation round. However, subject to the absolute values that can be recorded in each round, the sub-hypotheses can be tested by dint of a one-tailed matched-pairs t-test as the large number of observations assures robustness of the t-test to violations of the normality assumptions.

As stated in the previous section, the simulation is mainly performed for the network configurations listed as follows: $(|Y|, |Y^k|) = \{(2,2), (2,5), (3,2), (3,3), (3,4), (4,3), (4,4), (5,3)\}$. Tables 6.5 and 6.6 show the results of the simulation runs for each of the tested network configurations analyzing the relative number of service providers opting for m^{PRTF} and m^{ETF-1} (cp. Hypothesis 6.2). Tables 6.7 and 6.8 show the results for each of the tested configurations in terms of service provider utilities. In more detail, each round's utilities u_j^{PRTF} and u_j^{ETF-1} of service provider v_j are aggregated to an expected utility $\bar{E}(u_\varrho^m)$ for each market m^{PRTF} and m^{ETF} and for each service provider class

ϱ_h. Additionally, the results for larger networks in terms of $|Y^k|$ are to be found in Section B.1 in tabular form and will briefly be discussed in the following.

As a first step to approach Hypothesis 6.1, the relative number of the service provider classes that prefer m^{PRTF} over m^{ETF-1} is compared. Tables 6.5 and 6.6 provide quite clear results. In at least six out of nine classes, m^{PRTF} is preferred over m^{ETF-1}. For (2,5), (3,4), (4,4), and (5,3), and also for the configurations tested in Table B.1, the PRTF-based market is chosen more often than the market applying ETF-1 *in each of the service provider classes*. That is, based on these results, Hypothesis 6.2 can be accepted. However, as above-stated, this result may be distorted by the absolute utility values which need to be considered in order to eventually accept or decline Hypothesis 6.1.

Table 6.5: Average share $|m|_{rel}$ of service providers opting for m^{PRTF} and m^{ETF-1} (1). $|m|_{rel}$ per ϱ_h does not add up to 100% – the remaining share denotes the state in which service providers are indifferent between choosing m^{PRTF} and m^{ETF-1}.

	$\lvert m\rvert_{rel}$, (2,2)		$\lvert m\rvert_{rel}$, (2,5)		$\lvert m\rvert_{rel}$, (3,2)		$\lvert m\rvert_{rel}$, (3,3)	
	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$
ϱ_1	43.2%	28.4%	70.5%	10.6%	47.0%	31.0%	58.4%	21.4%
ϱ_2	33.1%	44.4%	66.5%	24.3%	39.0%	46.9%	52.5%	37.3%
ϱ_3	26.0%	52.1%	53.8%	41.8%	37.9%	51.8%	46.7%	47.4%
ϱ_4	48.1%	13.8%	56.3%	2.77%	50.2%	23.3%	61.4%	13.6%
ϱ_5	40.0%	32.5%	66.3%	11.0%	47.0%	36.2%	60.7%	24.7%
ϱ_6	36.7%	37.8%	63.3%	24.5%	43.9%	44.3%	56.4%	34.7%
ϱ_7	39.4%	7.97%	27.8%	0.40%	52.5%	15.2%	59.8%	6.53%
ϱ_8	49.4%	15.5%	43.2%	2.33%	53.3%	23.8%	61.5%	14.7%
ϱ_9	42.9%	25.3%	55.4%	7.95%	52.7%	33.5%	61.5%	23.4%

Absolute utilities of a service provider when deciding upon entering m^{PRTF} or m^{ETF-1} are tested in Hypothesis 6.3 for every service provider class ϱ_h as shown in Tables 6.7 and 6.8. The asterisks indicate that the expected utility $\bar{E}(u_\varrho^{PRTF})$ of service providers in the PRTF market is significantly higher that their expected utility $\bar{E}(u_\varrho^{ETF-1})$ in the ETF-1 market.

Assuming that service provider types are equally likely, the underlying simulation shows that at least 66.7% of the service providers significantly prefer m^{PRTF} as shown in the lowermost row of Tables 6.7 and 6.8 (since $\bar{E}(u_\varrho^{PRTF}) > \bar{E}(u_\varrho^{ETF-1})$). For all tested network configurations, either six or seven out of nine service provider classes opt for the PRTF-based market. In larger network configurations as shown in Table B.1, the tendency towards choosing m^{PRTF} rises; in (2,8) and (2,10), 88.9% of the service provider classes would opt for it, only the very "best" class ϱ_3 prefers m^{ETF-1}.

The evaluation of the data brings about another characteristic of the PRTF: in network configurations that feature less service providers per candidate pool, less service provider classes are attracted in general while in configurations with a larger number of services per candidate pool, statistical tests turn out to be more distinct in terms of the tested hypotheses. That is, there is a trend to be observable towards

Table 6.6: Average share $|m|_{rel}$ of service providers opting for m^{PRTF} and m^{ETF-1} (2). $|m|_{rel}$ per ϱ_h does not add up to 100% – the remaining share denotes the state in which service providers are indifferent between choosing m^{PRTF} and m^{ETF-1}.

	$|m|_{rel}$, (3,4)		$|m|_{rel}$, (4,3)		$|m|_{rel}$, (4,4)		$|m|_{rel}$, (5,3)	
	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$
ϱ_1	68.1%	14.3%	63.3%	23.1%	72.4%	15.9%	66.1%	24.4%
ϱ_2	61.6%	29.4%	54.3%	37.6%	64.4%	28.6%	58.6%	36.0%
ϱ_3	52.8%	41.2%	47.4%	47.7%	54.3%	41.0%	49.7%	47.1%
ϱ_4	67.3%	6.77%	65.8%	13.8%	70.4%	9.59%	67.5%	15.2%
ϱ_5	65.9%	18.3%	63.6%	23.6%	70.0%	18.9%	66.1%	24.1%
ϱ_6	64.5%	27.1%	58.7%	33.6%	65.7%	27.3%	59.5%	33.9%
ϱ_7	59.8%	2.84%	61.8%	8.93%	67.9%	3.54%	66.3%	9.93%
ϱ_8	63.5%	8.23%	62.9%	13.5%	70.6%	8.75%	68.2%	15.6%
ϱ_9	63.6%	17.2%	61.6%	24.9%	70.3%	16.4%	64.1%	24.1%

a significant attraction of more service provider classes in network configuration with a higher $|Y^k|$ (cp. also Section B.1). On the other hand, the absolute average utility of service providers declines in larger networks due to the larger number of service providers potentially receiving a slice of the PR cake. Applying the ETF-1, the surplus is always distributed among allocated service providers. While the absolute amount of money granted to service providers remains unchanged, service providers' *expected* utilities also decrease when applying the ETF-1 due to a generally decreasing probability of allocation.

To summarize, both Hypothesis 6.2 and Hypothesis 6.3 can be accepted. Therefore, Hypothesis 6.1 also applies subject to the assumptions made in this simulation.

Generally, it is clear that not all of the service providers can be attracted. This result is straight forward since both PRTF and ETF-1 distribute the same surplus $\Delta = \mathcal{U}_{F^*}$. Therefore, if some of the service providers receive a larger share of it, others *must* be worse off. It is obvious that the most competitive service providers, roughly represented by price-quality combinations with $p_{ij} < q_j$ expect a higher payoff in m^{ETF-1} than in m^{PRTF}. However, service providers with intermediate price and quality tend to choose the PRTF market, likewise vendors that offer higher prices but lower quality. The latter class of agents can still be beneficial to an SVN as long as service providers attached to it make valuable contributions to the overall system. Furthermore, such providers contribute to the variety of the network, making it more attractive for service customers. It can be concluded that the PRTF systematically fosters *healthy network growth* – all kinds of service providers that yield a positive value to the network shall be remunerated. That way, variety and stability, which is valued and honored by customers when deciding on which market to enter [76], is increased. A continuously granted surplus to such service providers has the potential to ensure that they will also remain in the network.

By the sheer number of attracted service providers, the PRTF-based market is more likely to cover the whole range of functional and non-functional requirements that meet the request made by the customer. On the other hand, it is consider-

Table 6.7: Expected utilities of service provider classes in the PRTF and the ETF-1 market subject to different network configurations (1). * denotes significance at the level of p=0.1, ** denotes significance at the level of p=0.01. AR^{PRTF} stands for attraction rate of the PRTF-based market.

	$\bar{E}(u_\varrho^m)$, (2,2)		$\bar{E}(u_\varrho^m)$, (2,5)		$\bar{E}(u_\varrho^m)$, (3,2)		$\bar{E}(u_\varrho^m)$, (3,3)	
	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$
ϱ_1	0.304**	0.288	0.130**	0.110	0.305*	0.297	0.212*	0.204
ϱ_2	0.474	0.536	0.226	0.241	0.409	0.498	0.309	0.372
ϱ_3	0.606	0.711	0.329	0.427	0.496	0.601	0.397	0.500
ϱ_4	0.217**	0.148	0.069**	0.029	0.253**	0.216	0.172**	0.123
ϱ_5	0.365**	0.346	0.132**	0.098	0.363*	0.349	0.243*	0.232
ϱ_6	0.432*	0.424	0.205*	0.195	0.422	0.454	0.317	0.324
ϱ_7	0.146**	0.075	0.025**	0.005	0.220**	0.143	0.119**	0.051
ϱ_8	0.245**	0.160	0.051**	0.022	0.283**	0.224	0.178**	0.126
ϱ_9	0.326**	0.256	0.083**	0.041	0.343**	0.312	0.231**	0.197
AR^{PRTF}	77.8%		77.8%		66.7%		66.7%	

Table 6.8: Expected utilities of service provider classes in the PRTF and the ETF-1 market subject to different network configurations (2). * denotes significance at the level of p=0.1, ** denotes significance at the level of p=0.01. AR^{PRTF} stands for attraction rate of the PRTF-based market.

	$\bar{E}(u_\varrho^m)$, (3,4)		$\bar{E}(u_\varrho^m)$, (4,3)		$\bar{E}(u_\varrho^m)$, (4,4)		$\bar{E}(u_\varrho^m)$, (5,3)	
	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$
ϱ_1	0.160**	0.147	0.227*	0.214	0.177**	0.161	0.244*	0.234
ϱ_2	0.245	0.290	0.297	0.364	0.239	0.294	0.295	0.357
ϱ_3	0.321	0.422	0.369	0.484	0.301	0.405	0.354	0.475
ϱ_4	0.115**	0.061	0.176**	0.127	0.135**	0.088	0.186**	0.133
ϱ_5	0.185**	0.161	0.237**	0.214	0.191**	0.172	0.239**	0.215
ϱ_6	0.241*	0.232	0.305	0.305	0.240*	0.229	0.296	0.295
ϱ_7	0.075**	0.025	0.139**	0.080	0.087**	0.029	0.141**	0.089
ϱ_8	0.113**	0.068	0.166**	0.124	0.118**	0.063	0.186**	0.139
ϱ_9	0.163**	0.117	0.227**	0.195	0.159**	0.106	0.220**	0.180
AR^{PRTF}	77.8%		66.7%		77.8%		66.7%	

ably more uncertain if a customer request can be accomplished by the two to three remaining classes of service providers that did not opt for m^{PRTF} in the first place. This is especially true for rather small networks. Therefore, as stated above, it can be assumed that customers prefer larger, more variable networks over networks offering highly efficient services, however, lack functionality. Assuming that customers opt for the market that is more variable, previously non-attracted service providers may be likely to be "forced" to also join m^{PRTF} due to the larger customer base.

6.4.4 Summary & Implications

Network growth is a key factor to establish a sustainable business. The SVN connects two market sides, service customers and service providers. Each of the two market sides benefit from participants joining the other network side [14]. Not only the quantity of customers will boost the success of the network, but also the quantity and complementarity of sellers as well as the quality of their offerings. Both sides of the market positively value the number of participants on the other market side. Service customers benefit from a larger number of heterogenous service providers leading to increased variety. However, sellers are only willing to register if they expect to face many customers in the market [62].

A result from the previous section was that, as a matter of the same surplus distributed in both the PRTF and the ETF-1 market, some of the service provider classes must be worse off when operating in m^{PRTF} than when selling their services in m^{ETF-1}. From a bird's eye view, attracted service providers do not necessarily have to be the most competitive ones as long as the *mass of attracted vendors assure that a sufficiently large number of customers enter the platform*. As shown in Section 6.4.3.2, the co-opetition mechanism induces intensified growth on provider-side in each of the tested network configurations. The quantity of attracted service providers is likely to lead to the attraction of service customers that base their decision to enter a market upon the expected future size of the network [187]. Thereby, they activate network effects which *provide additional value for vendors*, that is, increase their expected utilities for joining the network and actively participate in it. This effect may also include service providers that were not attracted by the m^{PRTF} in the first place. That way, the above-described circle of increasing utility for both market sides can be fueled.

6.5 Summary

Each of the presented properties are of particular importance in SVNs. The presented *fairness* property in connection with *cooperational monotonicity* fundamentally enables the implementation of transfers granted to a set of service providers that also includes non-allocated participants. On the one hand, cooperative aspects in SVNs are considered via the assignment of value functions on a path level and the very remuneration of alternative service offers based on their contribution to the overall network. By valuing not only allocated paths, but also alternatives that would also create utility if the best path was not in place, the PRTF also accounts for the service providers' *readiness* to continuously keep ready their services for delivery. Fairness ensures that these payoffs are generally perceived evenhanded by service providers which is a prerequisite for their participation. On the other hand, competition is retained by rewarding individual contributions to the network. Cooperational monotonicity thereby ensures that an increase in a service provider's individual efficiency must be rewarded with an at least identical or a larger payoff. That way, effective incentives to improve and innovate services in the SVN are given.

Inducing a fully intermeshed SVN as a stable state, the co-opetition mechanism fosters *interconnectedness* in the network, which is a prerequisite for complementarity: the more alternative links connect available services, the greater the variety of complex service instances that can be offered. Therefore, incentives for link formation can be interpreted as the key enabler for complementarity. Transferring this result from a single, customer-requested SVN to the whole pool of services registered with an SVN, the long valley's exponentially growing number of possible service offerings is optimally fueled (cp. also Section 2.2). Thereby, the co-opetition mechanism supports one of the key value propositions of SVNs and the long valley.

The co-opetition mechanism's ability to foster *network growth* was shown by comparing the power ratio-based transfer function to an allocation-based payment scheme based on Parkes et al. [260] that does not set particular incentives besides its emphasize on competition. By setting incentives for the bulk of service providers, the co-opetition mechanism is likely to provide the variety of services that is demanded by the customer. Thereby, increasing returns for service providers can be initiated – even if the most effective service providers are not incentivized to join an PRTF-based SVN in the first place. Their participation may be caught at a later stage after a certain network size is reached due to increased valuation for larger networks owed to their larger customer base.

Recall that the network design goals discussed in this chapter account for the "downgrading" of some classic mechanism design goals as second-tier properties. The PR-based transfer function is not particularly designed to fulfill incentive compatibility – and therefore, inevitably dismisses allocation efficiency to a certain extent (cp. Section 3.1.4). Nevertheless, as for instance shown in Section 6.1.5, incentive compatibility is connected to fairness properties in terms of the extensibility of fairness from the PR to the entire transfer function. Thus, although being a second-tier-property, incentive compatibility still remains in the close focus and will be evaluated in detail as the core contribution of the next chapter.

Chapter 7

Classic Mechanism Design Objectives

The network mechanism design perspective centers on objectives that arise from network design (cp. Section 4.1.1). Such objectives may overbalance some classic mechanism design desiderata in the first place, however, this does not mean that the latter can simply be neglected. On the one hand, budget balance and individual rationality as classic properties are essential in order to guarantee a sustainable business. On the other hand, incentive compatibility and allocative efficiency are not systematically targeted by the PR-based payments. Incentive compatibility was traditionally seen as a requirement rather than a desideratum in mechanism design, in itself being technically achievable in every mechanism according to the revelation principle [131, 234]. This notion has changed with the awareness that the revelation principle may be quite complex to implement and that "good enough" results, either in terms of economic or computational efficiency [260, 245], may be achieved without enforcing truth-telling. Networked mechanism design takes the same line, with "efficiency" being attributed to a healthy network evolution.

Nonetheless, it would be quite shortsighted to design a mechanism that completely loses track of incentive compatibility and allocative efficiency – for several reasons: first, incentive compatibility is linked to fairness in the broader sense (cp. Section 6.1.5). Second, a high degree of allocative efficiency is certainly desirable in a way that it allocates those network participants that assign the highest value to their inclusion in a transaction, thereby remunerating their high performance, especially as the collective of service providers is already adorned with the PR payoffs.

As shown in Sections 5.4 and 6.1.1, budget balance is fulfilled by design: the co-opetition mechanism collects and disburses the same amount of money from and to the platform participants. Individual rationality as a second required property accounting for voluntary participation of service providers will be discussed in Section 7.2, based on the simulatively acquired results on service providers' optimal bidding strategies (cp. Section 7.1). The latter are primarily scrutinized in a series of agent-based simulations in order to shed light on the co-opetition mechanism's vulnerability to strategic manipulation with respect to the service providers' types. In addition, effects on allocative efficiency caused by such deviation from truth-telling will be explored.

Again, the analytic and numerical evaluations conducted in the current chapter are based on both the notation of the SVN formalization (cp. Section 2.2.3) and the bidding language and further notation used for defining the co-opetition mechanism's allocation and transfer function as introduced in Sections 5.1 and 5.2).

7.1 Incentive Compatibility & Allocative Efficiency

According to Definition 3.12, a mechanism is said to be incentive compatible if it is a direct-revelation mechanism and the participants want to reveal their true preferences in equilibrium. Obviously, as noted in Section 5.4, the co-opetition mechanism directly reveals agents' types – no matter if truthful or not in the first place. However, as will be shown in the current section, truth-telling in equilibrium cannot be stated in an analytical sense. If incentive compatibility is not met, the co-opetition mechanism also loses allocative efficiency as a guaranteed property by definition (cp. Section 3.1.4).

This section scrutinizes the co-opetition mechanism's vulnerability to strategic behavior at the service provider-side. Due to the variety of parameters and the complexity of the underlying transfer function – the complexity of calculating the power ratio for n services is in $\mathcal{O}(2^n)$ – analytic considerations are only possible to a very limited extent. In such interwoven environments, the complex analytical apparatus oftentimes impedes theoretical evaluations that properly include the variety of interrelations [192]. Thus, in numerical simulations, restricting assumptions made as a remedy to calculate theoretic solutions can be relaxed in order to reproduce interactions in SVNs more realistically [6, 315]. In this thesis, a series of agent-based simulations will be consulted to analyze the degree of bid manipulation that is beneficial to service providers. Extracting possible equilibrium strategies from the bidding strategy evaluation, a comparison of outcomes and their overall utility with and without manipulation is conducted in order to review the co-opetition mechanism's degree of allocative efficiency.

The remainder of this section is structured as follows: Section 7.1.1 will both formally and exemplarily show that the co-opetition mechanism is not incentive compatible, followed by considerations on allocative efficiency. The degree of manipulation robustness will be assessed in an agent-based simulative approach outlined in Sections 7.1.2 and 7.1.3: different simulation series are run in order to approach the equilibrium strategies of service providers and to be able to make statements on the level of efficiency that can be reached by the co-opetition mechanism.

7.1.1 Analytic Considerations

The distribution of value according to the power ratio combined with the allocation-based component is generally not designed to extract truthful bids from service providers. A counterexample is provided in Example 7.1. Applying the revelation principle as one of the most striking results of mechanism design, any mechanism can be transformed into an equivalent incentive compatible direct-revelation mechanism. However, as indicated in the introduction to this chapter, the revelation principle, per se, is a theoretic result: the construction of the equivalent mechanism can become arbitrarily complex. Moreover, although the resulting mechanism will be direct in contrast to, for instance, an ascending auction, it can still require multiple iterations. This is not desirable for the co-opetition mechanism in which complex negotiation protocols counteract the dynamics of SVNs and the long valley. The settlement shall be made directly after the service customer and the set of service providers have submitted their one (and single) bid.

Thus, the co-opetition mechanism in its presented form shall remain unchanged, thereby accepting vulnerability to manipulation.

7.1.1.1 Bidding Strategies

This section includes an analysis of service providers' bidding strategies as they are articulated in their bids $b_{ij} \in \mathcal{B}$, taking the service customer's preferences as given (cp, Assumption 5.2). The following analytical evaluation considers price bids only: the quasi-linear structure of the scoring function as introduced in Equation (5.1) allows for a substitution of quality-related bids and price bids under quite weak assumptions. Subject to the simplifying assumption that the utility granted by a service provider to the system is monotonically increasing with a higher quality offered and monotonically decreasing when the offered quality is lower, strategies for setting prices and quality attributes can be substituted.[1]

For both allocated and non-allocated service providers, *transfers must be independent of their bidding strategy in order to be indifferent between any other strategy and truth-telling* [140, 257]. In case of truth-telling, we can set $p_{ij} = c_{ij}$ and the utility u_k for a service provider $n_k \in N$ evolves as follows:

$$\begin{aligned} u_k &= \sum_{e_{ij}|e_{ij}\in E(W^*),v_j\in\sigma(k)} p_{ij} - \sum_{e_{ij}|e_{ij}\in E(W^*),v_j\in\sigma(k)} c_{ij} + \sum_{e_{ij}|v_j\in\sigma(k)} \phi_j \\ &= \sum_{e_{ij}|v_j\in\sigma(k)} \phi_j \end{aligned} \tag{7.1}$$

That is, assuming truth-telling, the service providers' utilities are solely comprised of their power ratios. The following analysis shows that both allocated and non-allocated service providers' utilities are dependent on their own price bids. Thus, analytically, truth-telling cannot be a weakly dominant strategy. For simplicity, it is assumed that each service provider n_k owns exactly one service v_j, that is, $\sigma(n_k) = \{v_j\}$ and $\bar{\sigma}(v_j) = n_k$.

1. $v_j \notin W^*: \ u_j = \phi_j$. v_j's power ratio is assembled by its weighted marginal contribution to all internal cooperations $S_m \in S$. If $\phi_j > 0$, v_j is a part of at least one complex service $F_l \in F$, which again determines the value functions of internal cooperations. Since $\mathcal{U}_{F_l} = \sum_{e_{ij}\in E(W_l)} p_{ij}$ for $v_j \in W_l$, $e_{ij} \in E(W_l)$, u_j depends on the service's price p_{ij}.
2. $v_j \in W^*$, $e_{ij} \in E(W^*): \ u_j = p_{ij} - c_{ij} + \phi_j$. The price bid is included proportionally in the service's power ratio and therefore does not cancel out the actual

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[1] This simplification will be made in some places of Section 7.1 in order to handle the complexity of the conducted evaluations.

price bid received from t_j^1. In more detail, ϕ_j can be subdivided into the overall amount of money to be distributed via the PR ($\Delta = \mathcal{U}_{F^*}$) and v_j's *relative* share in Δ, denoted as $\zeta_j \in [0;1]$. Then,

$$\begin{aligned} u_j =& p_{ij} - c_{ij} + \zeta_j \cdot \Delta \\ =& p_{ij} - c_{ij} + \zeta_j \cdot (\alpha \cdot \mathcal{Q}(\cdot) - \mathcal{P}_{F^*}) \\ =& \underbrace{p_{ij} \cdot \underbrace{(1-\zeta_j)}_{>0}}_{\text{dependent on } p_{ij}} + \zeta_j \cdot (\alpha \cdot \mathcal{Q}(\cdot) - \sum_{e_{lk} \in E(W^*) \setminus \{e_{ij}\}} p_{lk}) - c_{ij} \end{aligned} \tag{7.2}$$

Therefore, other than, for instance, in a second-price-sealed-bid auction , deviation from truth-telling can be beneficial [199]. For example, the complex service auction (CSA) as presented in Blau [45] does not allow for beneficial deviation on the service provider-side (cp. Section 4.3).[2]

Getting back to the co-opetition mechanism, Figure 7.1 illustrates the service providers' manipulation strategies and corresponding utilities in more detail, comparing each of them to a truth-telling strategy. u_j^{truth} shall denote v_j's utility in case of truth-telling while u_j^{dev} stands for v_j's utility when stating a price other than the actual costs.

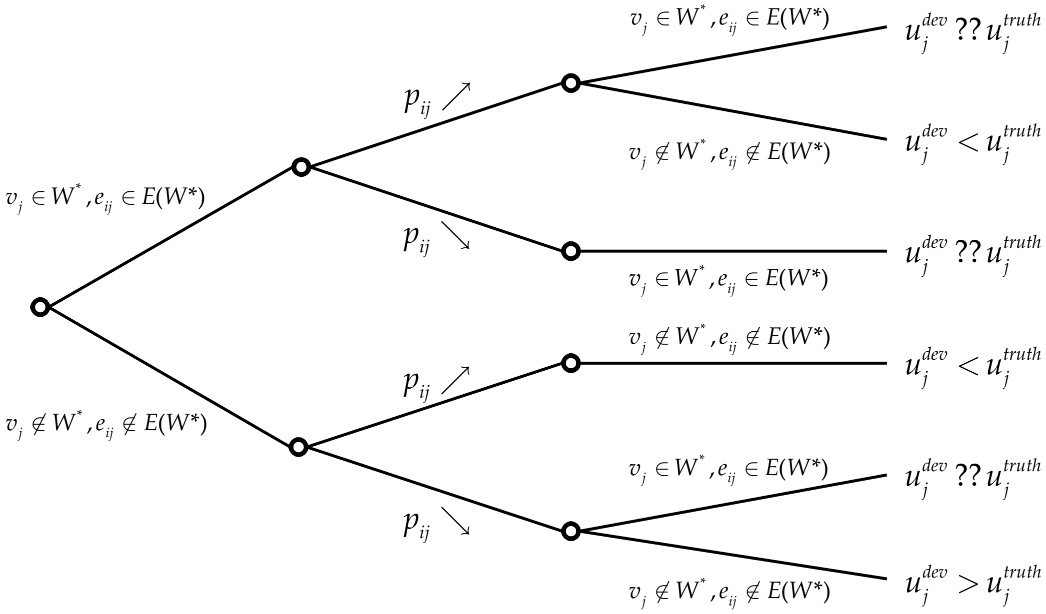

Figure 7.1: Bidding strategies of an arbitrary service provider

Focussed on a *single service provider to deviate from truth-telling*, two fundamental cases need to be considered in order to evaluate the result of different strategies. First, v_j is allocated via one of its links if reporting its cost truthfully in the price bid. Second, playing a truth-telling strategy, v_j is not part of the allocated complex service.

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[2] However, in Blau [45], this statement only holds if assuming no strategic behavior of the customer (cp. also Assumption 5.2).

1. Playing a truth-telling strategy, v_j is allocated via its link e_{ij}.
    (a) In this case, overstating the value can lead to both a profit or a loss. If, after deviating, v_j is still allocated, its profit or loss depends on the impact of the PR. By overstating, v_j would realize a profit from t_j^1 since $p_{ij} > c_{ij}$, however, incur a loss from t_j^2 since a higher price diminishes the utility of the complex services that include e_{ij} and therefore decreases the PR. This effect is exemplarily illustrated in Example 7.1 (cp. Table 7.2). If v_j drops off the allocation after increasing its price, $u_j^{truth} > u_j^{dev}$ will definitely hold due to a decreased PR whilst simultaneously the utility from t_j^1 remains unchanged.
    (b) Undercutting the true costs also leads to an ambivalent result. $p_{ij} < c_{ij}$ will lead to a loss in t_j^1, however, t_j^2 will rise due to the lower price compared to truth-telling.
2. Playing a truth-telling strategy, v_j is not allocated via its link e_{ij}
    (a) Overstating the value would inevitably lead to a decreased utility since it is not possible to be allocated with a higher price if not being allocated before. t_j^2 would additionally decrease due to the higher price.
    (b) Undercutting the true costs again yields an ambiguous utility. If undercutting leads to a situation in which v_j is allocated, $p_{ij} < c_{ij}$ will lead to a loss in t_j^1. It is not clear if this loss can be compensated for via the rising PR (cp. Example 7.1, Table 7.3). On the other hand, if a decreased price does not trigger an allocation, $u_j^{dev} > u_j^{truth}$ will definitely hold.

Example 7.1 [DEVIATION FROM TRUTH-TELLING]. *Consider the exemplary, simplified SVN with* $|Y| = 2$ *and* $|V| = |N|$ *as displayed in Figure 7.2.*[3] *Assume a customer's willingness to pay of* $\alpha = 5$ *and bid prices of the involved service providers as shown in Figure 7.2.*

If all service providers reveal their internal costs truthfully as bid prices, the complex service $F_1 = F^{*truth} = (\{v_1, v_3\}, \{e_{s1}, e_{13}\})$ *with* $\mathcal{P}_{F_1} = 3$ *is allocated and* $\Delta^{truth} = 2$ *is distributed via the power ratio. Payoffs and utilities assemble as shown in Table 7.1 according to Equation* (5.21)*:*

Table 7.1: Bidding strategies: Transfers and utilities in case of truth-telling

	v_1	v_2	v_3	v_4
$t_j = t_j^1 + t_j^2$	1+0.75	0+0.25	2+0.75	0+0.25
u_j^{truth}	(1+0.75)-1=0.75	0.25	(2+0.75)-2=0.75	0.25

Now assume that service provider n_1 *deviates from its true costs, charging* $p_{s1} = 1.5$ *for its service* v_1. F_1 *is still allocated, however, due to the increased price* $\mathcal{P}_{F_1} = 3.5$*, only* $\Delta = 1.5$ *is left to be distributed via the PR. The new transfers and profits evolve as shown in Table 7.2 and can be compared to the results in case of truth-telling.*

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[3] As shown in Section 6.3, the fully intermeshed SVN is a stable result. Example 7.1 is deliberately simplified so that effects of manipulated bids can easily be tracked.

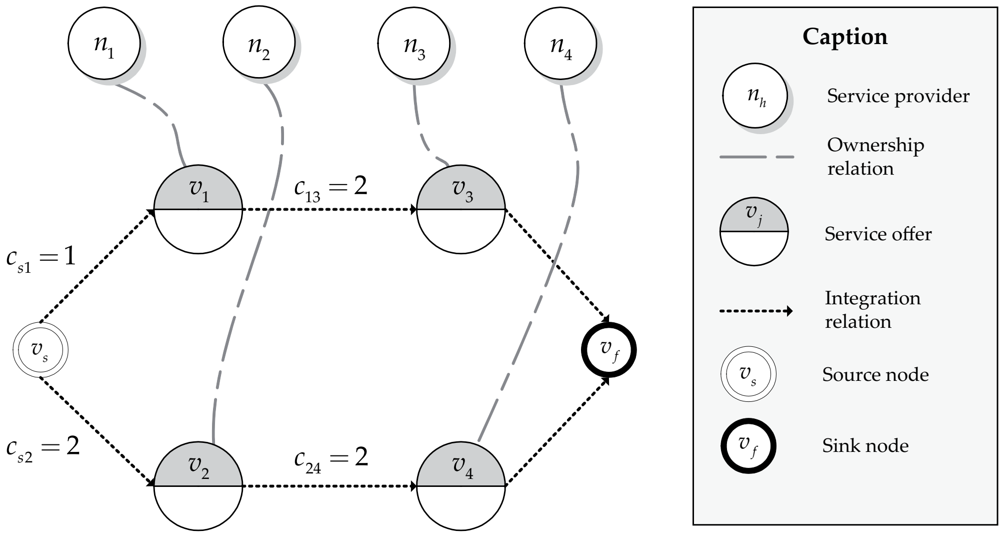

Figure 7.2: Bidding strategies: A simple SVN example

Table 7.2: Bidding strategies: Transfers and profits in case of unilateral deviation – gaining through overbidding

	v_1	v_2	v_3	v_4
$t_j = t_j^1 + t_j^2$	1.5+0.5	0+0.25	2+0.5	0+0.25
u_j	(1.5+0.5)-1=1	0.25	(2+0.5)-2=0.5	0.25

Two basic results can be observed. First, v_1 increases its utility when deviating from truth-telling ($u_j^{truth} < u_j^{dev}$). Second, v_3's utility is decreasing although v_3 itself did not manipulate. Therefore, a service provider's strategy is also heavily dependent on its assumptions on what the other vendors choose to do.

For a different outcome, again consider the SVN as introduced in Figure 7.2. This time assume that service provider n_2 deviates from its true costs, charging $p_{s2} = 0.5$ for its service v_2. Thus, the allocated complex service switches from $F_1 = F^{*truth}$ to $F^* = F_2 = (\{v_2, v_4\}, \{e_{s2}, e_{24}\})$. Due to the lower price $\mathcal{P}_{F_2} = 2.5$, Δ increases to 2.5. Transfers and utilities evolve as shown in Table 7.3.

Table 7.3: Bidding strategies: Transfers and profits in case of unilateral deviation – losing through underbidding

	v_1	v_2	v_3	v_4
$t_j = t_j^1 + t_j^2$	0+0.5	0.5+0.75	0+0.5	2+0.75
u_j	0.5	(0.5+0.75)-1.5=-0.25	0.5	(2+0.75)-2=0.75

In this example, v_2 decreased its utility by deviating from truth-telling and switching from being non-allocated to being allocated. Interestingly, in this case, v_4's utility increased as a result of v_2's changing action.

7.1.1.2 Allocative Efficiency

As incentive compatibility in equilibrium is not met, allocative efficiency cannot be guaranteed either. Therefore, the degree of allocative efficiency reached by the co-opetition mechanism is based on the strategies played by the service providers. Recall that a mechanism is defined as allocatively efficient if its choice, that is, transferred to the SVN scenario, the allocated complex service $F^* \in F$, maximizes the total valuation over all agents. Since $U^{SC}_{F^*} = 0$ and due to the neutrality of the platform operator, efficiency considerations can be pooled to the service provider-side. Therefore, without loss of generality, assuming that $|V| = |N|$, Equation (3.1) can be reformulated as follows:[4]

$$\sum_{v_j \in V} u_j(\theta_j, F^*, t_j) \geq \sum_{v_j \in V} u_j(\theta_j, F', t_j) \; \forall F' \in F,\; F^* \neq F' \tag{7.3}$$

with

$$\sum_{v_j \in V} u_j(\theta_j, F^*, t_j) = \Delta + \sum_{e_{ij} \in E(W^*)} p_{ij} - \sum_{e_{ij} \in E(W^*)} c_{ij} = \underbrace{- \sum_{e_{ij} \in E(W^*)} c_{ij}}_{\text{Valuations}} + \underbrace{\sum_{v_j \in V} t_j}_{\text{Transfers}} \tag{7.4}$$

Again, only consider prices and costs are considered as argued for in the preceding section. According to Section 3.1.3, assuming quasi-linear preferences, it is sufficient to consider the valuations $\sum_{v_j \in V} \tau_i(\cdot)$. According to Definition 3.4 and directly following from Equation (7.4),

$$\sum_{v_j \in V} u_j(\theta_j, F^*, t_j) = \sum_{v_j \in V} \tau_j(\theta_j, F^*) + \sum_{v_j \in V} t_j(\theta_j) \tag{7.5}$$

If every service provider states its true type for owned services, the cheapest path $o = F^{*truth}$ is allocated. That is,

$$\sum_{v_j \in V} \tau_j(\theta_j, F^{*truth}) = \max_{F_l \in F}\Big(- \sum_{i,j:\; e_{ij} \in E(W_l)} c_{ij}\Big) \tag{7.6}$$

From Equation (7.6), it is obvious that the following equation must always hold:

$$\underbrace{\sum_{v_j \in V} \tau_j(\theta_j, F^{*truth})}_{\max\limits_{F_l \in F}(- \sum\limits_{i,j:\; e_{ij} \in E(W_l)} c_{ij})} \geq \underbrace{\sum_{v_j \in V} \tau_j(\theta_j, F')}_{\max\limits_{F_l \in F \setminus F^{*truth}}(- \sum\limits_{i,j:\; e_{ij} \in E(W_l)} c_{ij})} \qquad \forall F' \in F, F^{*truth} \neq F' \tag{7.7}$$

Therefore, truth-telling of service providers leads to the allocative efficient choice. Based thereupon, one can show that the allocation function picks the efficient path *whenever the cheapest path is allocated – regardless of service providers deviating from truth-telling or not*. In more detail, as long as a deviation of participants does not lead to a change in the allocated complex service F^{*truth}, the welfare $\mathcal{W}$ of the system (cp. Equation 5.9) remains unchanged. Transfers are merely reallocated amongst service providers with their total staying the same. This result is in line

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[4] Note that θ_j denotes v_j's type as opposed to the notation in Chapter 5, where θ symbolizes the customer's preferences.

with a theoretical result which states that all efficient choices of a quasi-linear mechanism need to involve the same allocation and may only differ in how transfers are distributes [296].

Consider a situation in which truth-telling allocates $o = F^{*truth}$. Further, Δ^{truth} shall denote the distributed surplus via the PR, while $\mathcal{W}^{truth}$ shall be the welfare that is generated, both assuming truth-telling.

1. First, consider a situation in which deviation from the true type does not change the allocated path, that is, $o = F^{*truth}$ still holds.
    (a) Assume that some of the allocated services decrease their prices, letting Δ^{truth} increase, which leads to $\Delta' = (1 + x) \cdot \Delta^{truth}$. Then, the deviating allocated services realize a loss from t^1 in the amount of $x \cdot \Delta^{truth}$ which in sum exactly cancels out the overall increase in t^2: $\mathcal{W}' = (1 + x) \cdot \Delta^{truth} - x \cdot \Delta^{truth} = \mathcal{W}^{truth}$.
    (b) Now assume that some of the allocated services increase their prices, letting Δ^{truth} decrease, which leads to $\Delta'' = (1 - x) \cdot \Delta^{truth}$. Then, the deviating allocated services realize a profit from t^1 in the amount of $x \cdot \Delta^{truth}$ which in sum exactly cancels out the overall decrease in t^2: $\mathcal{W}'' = (1 - x) \cdot \Delta^{truth} + x \cdot \Delta^{truth} = \mathcal{W}^{truth}$.
2. Now assume that deviation from the true type changes the allocated path to $o = F' \neq F^{*truth}$.
    (a) If some of the previously allocated service providers increase their prices, thereby causing a switch of the allocated path from F^{*truth} to F', the PR-based payments decrease to $\Delta''' \leq \Delta^{truth}$, since $\mathcal{U}_{F'} \leq \mathcal{U}_{F^{*truth}}$. As t^2 of the providers that dropped off the allocated path must have decreased, $\mathcal{W}''' \leq \mathcal{W}^{truth}$ must necessarily hold.
    (b) Assume that some of the previously non-allocated services decrease their price which lets a different path $F'' \neq F^{*truth}$ be allocated. Then, the PR-based payments increase to $\Delta^{(4)} \geq \Delta^{truth}$ since $\mathcal{U}_{F''} \geq \mathcal{U}_{F^{*truth}}$. Obviously, the deviating allocated services realize a loss from t^1 which must be at least as high as $\Delta^{(4)} - \Delta^{truth}$. Therefore, $\mathcal{W}^{(4)} \leq \mathcal{W}^{truth}$ must hold.

7.1.1.3 Conclusion

To summarize the considerations on bidding strategies: even if service providers definitively knew if they were allocated or not, three of four branches in the decision tree shown in Figure 7.1 would not yield a distinct strategy implication. Besides service providers' own competitiveness and the other service providers' prices[5], four other parameters directly influence the bidding strategy.

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[5] This statement holds for the simplified setting that only considers prices. Analogously, the service configuration influences the bidding strategy if the simplifications above are not made.

- First, the *customer's willingness to pay* determines the absolute amount of money Δ distributed via the PR (cp. Equation 5.7).[6] In case of a high willingness to pay, PR-based payments can also be high, thereby overcompensating losses incurred by undercutting the true costs, and vice versa.
- Second, the *number of services per candidate pool* is a crucial factor for services to be allocated or not.
- Third, the *overall number of candidate pools and included services* determines the global competition for Δ.
- Finally, the *density d of the network*, which denotes the ratio of actual links and all possible edges in the SVN, determines the number of available complex service instances. Thereby, the probability of allocation as well as the service providers' shares in Δ are potentially influenced.

These parameters are proprietary knowledge of the platform operator and cannot be fully extracted by service providers from the bits of information that circulate in the SVN during the auction process (cp. Section 5.1.3). Therefore, service providers can only have an *expectation* of which SVN to form and a prior of which requester type is present. In order to grasp such different scenarios, strategic behavior of service providers within the co-operation mechanism is analyzed in a simulation-based approach.

For the following evaluation, keep in mind that the co-opetition mechanism yields an allocative efficient result whenever o allocates the complex service that maximizes $\mathcal{U}_{F_l}$ for all $F_l \in F$ *given true types of the services*. That is, allocative efficiency on service provider-side cannot only be stated in case of a truth-telling strategy played by each of the service providers, but also in case of deviating, as long as the best path given true types is allocated, that is

$$o = \underset{F_l \in F}{\operatorname{argmax}} \left(\alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) - \sum_{i,j:\ e_{ij} \in E(W_l)} c_{ij} \right) \tag{7.8}$$

However, allocative efficiency is universally guaranteed if and only if participants opt for a truth-telling strategy.

7.1.2 Simulation-based Assessment of Bidding Strategies

In analogy with Parkes et al. [260], two related simulations are conducted in order to analyze the service providers' strategies in the co-opetition mechanism. Firstly it is assumed that one service provider $n_k \in N$ unilaterally deviates from revealing its true type with respect to service $v_j \in V$ with $\bar{\sigma}(v_j) = n_k$ while all other service offers are submitted truthfully (cp. Section 7.1.2.2). Secondly, in Section 7.1.2.3 the simulation settings are varied to a situation which includes symmetric bidding strategies.

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[6] This statement holds true for the simplified setting that only considers α. Analogously, the other elements of the customer's type analogously influence Δ if the simplifications above are not made.

That is, it is assumed that if service provider n_k deviates from truth-telling by $x\%$ regarding all incoming links of $v_j \in V$ with $\bar{\sigma}(v_j) = n_k$, then every other service provider also manipulates all its bids by $x\%$.

For simplification and without loss of generality, $|V| = |N|$ shall hold such that service providers and services can be referred to interchangeably. Further, the analysis is restricted to bid prices since service configurations are fully monetized via the customer's willingness to pay and the scoring function.[7]

7.1.2.1 Benchmark: The ETF-2

In order to benchmark the results yielded by the co-opetition mechanism with respect to its robustness to manipulation and its allocative efficiency, it is compared to other mechanisms. On the one hand, the ETF-1 as introduced in Section 6.4.1 is consulted.

A second benchmark shall be a payment scheme that does not only reward service providers that are actually allocated, but also service providers on standby. Based on the *egalitarian rule* [340, 175], a scheme that distributes Δ equally among all services in the customer-specific SVN G, henceforth named ETF-2, shall serve as such a benchmark. Analogue to the ETF-1, the allocation function introduced in Definition 5.5 is adopted to the ETF-2.

Definition 7.1 [EQUAL TRANSFER FUNCTION FOR ALL PARTICIPATING SERVICES (ETF-2)]. *The ETF-2 distributes the system's surplus Δ in equal shares to all participating services $v_j \in V$:*

$$t_j^{E2} = \begin{cases} p_{ij} + \frac{1}{|V|}\Delta, & \text{if } v_j \in W^*, e_{ij} \in E(W^*) \\ \frac{1}{|V|}\Delta, & \text{otherwise} \end{cases} \tag{7.9}$$

Thus, the ETF-2 covers the cooperative element in SVNs, however, does not set any direct incentives for competition since each service provider receives an equal share of Δ, no matter if it is competitive or not. That is, while the PRTF could be tagged as somewhat *social*, the ETF-2 shows distinct tendencies of a *socialistic* scheme that rewards agents regardless of their productivity – with exception of the transfers made to allocated services accounting to their bids. In contrast, the ETF-1 is a competitive payment scheme which has a component that rewards allocated services in equal shares.

The ETF-2 thus represents a payment scheme that mandatorily *must* come off worse than the PRTF in terms of manipulation robustness. Consequently, the ETF-2 must be beaten by the PRTF as stated in the following hypothesis.[8]

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[7] Subject to the simplifying assumption that the utility granted by a service provider to the system is monotonically increasing with a higher quality offered and monotonically decreasing when the offered quality is lower, strategies for setting prices and quality attributes can be substituted.

[8] Hypothesis regarding the comparison PRTF vs. ETF-1 are not stated. The ETF-1 is consulted in order to learn how the PRTF performs against a purely competition-oriented payment rule. If, or in which cases the PRTF performs better than the ETF-1, cannot be stated reliably in advance.

Hypothesis 7.1 [MANIPULATION ROBUSTNESS]. *The PRTF is more robust against manipulation than the ETF-2.*

In other words, the PRTF needs to allow for lower profitable manipulation rates than the ETF-2. Hypothesis 7.1 will be analyzed by comparing the degree of manipulation that significantly improves service providers' utilities subject to the PRTF and the ETF-2.

7.1.2.2 Unilateral Strategies

Simulation Model

In the current simulation, the following parameters that influence service providers' strategies as listed in Section 7.1.1.3 are varied.

- 3 different levels of the customer's willingness to pay α, defined relatively to the number of candidate pools $|Y|$, are considered. These are $\alpha_1 \in U[0.5 \cdot |Y|;1 \cdot |Y|]$, $\alpha_2 \in U[1 \cdot |Y|;2 \cdot |Y|]$, and $\alpha_3 \in U[2 \cdot |Y|;4 \cdot |Y|]$. $U[x_1;x_2]$ denotes that a value is uniformly drawn from the interval $[x_1;x_2]$.
- Complex services including $|Y| = 2$, $|Y| = 3$, and $|Y| = 4$ candidate pools are considered.
- Without loss of generality, an equal count of services $|Y^k|$ per candidate pool Y^k is assumed, setting $|Y^k| \in \{2,3,4,5\}$.
- Finally, the network density is set to $d = 1.0$ as this is the equilibrium value for the co-opetition mechanism (cp. Section 6.3.2). This does not necessarily hold for the benchmarks. However, as full intermeshing reflects the ideal concept of service value networks and the long valley, $d = 1.0$ must also be the performance benchmark for the ETF-1 and the ETF-2.[9]

Each of the above-introduced scenarios, or network configurations, can be interpreted as an independent simulation. As argued for in Section 6.4.3, the number of candidate pools and service per candidate pool reflect a realistic situation in early SVNs. A configuration is denoted by the triple $(|Y|,|Y^k|,\alpha_i)$, indicating the number of considered candidate pools, the number of services per candidate pool, and the level of the customer's willingness to pay. All in all, 27 configurations are tested as listed in Table 7.4.

Table 7.4: Bidding strategies: Tested network configurations. $i \in \{1,2,3\}$

$\|Y\| = 2$	$\|Y\| = 3$	$\|Y\| = 4$
$(2,2,\alpha_i)$	$(3,2,\alpha_i)$	$(4,2,\alpha_i)$
$(2,3,\alpha_i)$	$(3,3,\alpha_i)$	$(4,3,\alpha_i)$
$(2,4,\alpha_i)$	$(3,4,\alpha_i)$	
$(2,5,\alpha_i)$		

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[9] In addition, the SVN's density was tested by means of a preceding sensitivity analysis, yielding that the density does not significantly influence the simulation result.

The tested topologies shall cover a variety of different real-world situations. The customer's willingness to pay varies from comparably low (α_1) to very high (α_3). The upper boundary of α_3, $4 \cdot |Y|$, reflects an unrealistically high willingness to pay in order to also capture "extreme" situations. Combined with the number of services per cluster, different market situations evolve: on the one hand, $(2,2,\alpha_3)$ depicts a situation that lacks competition in either way while $(2,5,\alpha_1)$ can be interpreted as a highly competitive situation with both harsh competition to be allocated and a customer whose willingness to pay is close to the fair market value.

For each of these configurations, a network topology G is generated, where costs c_{ij} are drawn randomly as follows: a mean $\mu_k \in U(0;1.0]$ for each candidate pool Y^k is drawn using a uniform distribution. For each candidate pool Y^k, the costs per link associated to each $v_j \in Y^k$ are taken from a Gaussian distribution $\mathcal{N}(\mu_k, \hat{\sigma})$. The standard deviation $\hat{\sigma} \in [0.05;0.25]$ assures realistic price spreads.[10] After initializing the network configuration (cp. Section 5.3.2), a service offer $v_j \in V$ in the SVN is randomly drawn. At first, its utility u_j^{truth} is computed, assuming that v_j truthfully reports its costs to the mechanism ($c_{ij} = p_{ij}$). Subsequently, the bid prices p_{ij} for all incoming links of v_j are manipulated from +100% (which equals a manipulation rate of $r = 1.0$) to −95% ($r = -0.95$) in steps of 5 percentage points. In each of the steps, the utility $u_j^{r_{uni}}$ yielded by the manipulation of p_{ij} by the rate r_{uni} is calculated and compared to the truth-telling utility, resulting in the utility ratio $R_j^{r_{uni}}$ as shown in Equation (7.10).

$$R_j^{r_{uni}} = \frac{u_j^{r_{uni}}}{u_j^{truth}} \tag{7.10}$$

If $R_j^{r_{uni}} > 1$, deviation at r_{uni} is beneficial to v_j. Note that, applying unilateral strategies, any other service $v_i \in V$ besides v_j is offered at true costs. Despite of the various different configurations, the number of variable parameters and their interdependencies are still high. To counteract high volatility and statistical noise in the simulation model, 5000 different topologies are evaluated within one configuration.[11] In each of them, a random service is picked and evaluated in terms of its bidding strategy. In order to identify the range in which deviating from truth-telling is beneficial for service providers, the statistical significance of the aggregated result over 5000 topologies is tested via a one-tailed matched-pairs t-test. The test analyzes the alternative hypothesis stated as follows: *Service providers benefit from manipulation at manipulation rate r while all other agents reveal their true type.* That is, for v_j, $u_j^{r_{uni}} - u_j^{truth} > 0 \Rightarrow R_j^{r_{uni}} > 1$ must be significantly met. Figure 7.3 depicts the stepwise procedure of the simulation.

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[10] The interval for $\hat{\sigma}$ still allows for considerable variance in the costs for the services. As quality issues are faded out, $\hat{\sigma} \in [0.05;0.25]$ conservatively represents real-world price differences for substitutive services.

[11] Compared to the simulation conducted in Section 6.4.3, services are not classified in different categories which justifies the smaller number of simulation rounds in this simulation. Further, a sensitivity analysis for selected network configurations showed that both 2500 and 10,000 rounds yield results that do not significantly differ from the results created by the simulation settings at hand.

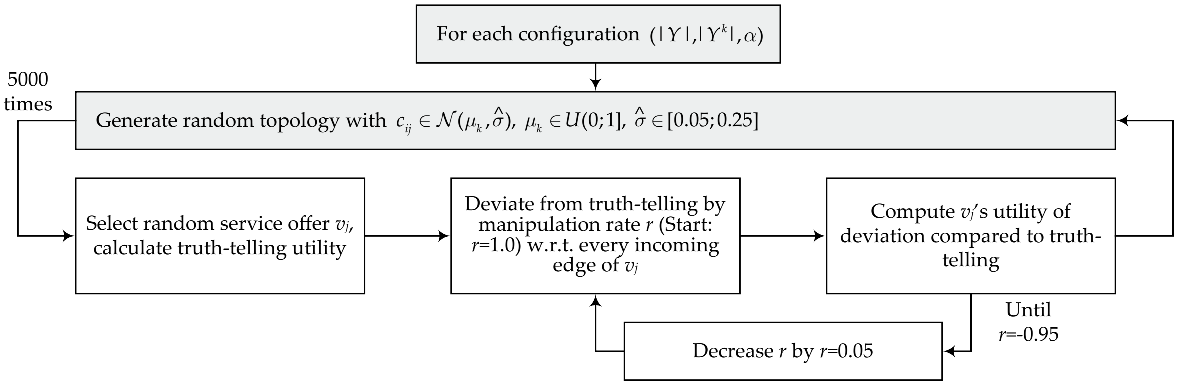

Figure 7.3: Bidding strategies: Simulation model (unilateral deviation)

From the utility ratios one can not only extract the manipulation rates that significantly increase a service provider's utility, but also the manipulation rate that in average maximizes u_j for each SVN configuration.

Due to the large size of analyzed topologies for each manipulation rate, interdependencies are likely to be canceled out and robustness of the t-test to violations of the normality assumption can be affirmed [268, 285, 56].

Simulation Results

In the following, selected results of the simulation are shown. First, the aggregated results for a minimal configuration with a high willingness to pay $(2,2,\alpha_3)$ are discussed. In more detail, for each payment rule (PRTF, ETF-1, and ETF-2) and at each manipulation level r, Table 7.5 outlines the mean absolute utilities AU, the mean utility ratio UR of single manipulating service providers, and the standard deviation SD of the mean absolute utility. The row that includes the data for truth-telling is highlighted in gray.

Table 7.5: Utility of an arbitrary service provider assuming unilateral manipulation in $(2,2,\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.448	0.826	0.222	0.273	0.500	0.518	0.540	0.996	0.189
0.95	0.453	0.835	0.221	0.276	0.506	0.520	0.541	0.998	0.189
0.90	0.457	0.842	0.219	0.280	0.512	0.523	0.541	0.998	0.188
0.85	0.463	0.852	0.218	0.287	0.524	0.528	0.543	1.000	0.187
0.80	0.467	0.861	0.217	0.293	0.536	0.532	0.543	1.002*	0.187
0.75	0.471	0.868	0.215	0.299	0.547	0.537	0.543	1.002*	0.186
0.70	0.477	0.879	0.214	0.306	0.559	0.541	0.545	1.004**	0.186
0.65	0.482	0.888	0.212	0.313	0.574	0.545	0.545	1.006**	0.185
0.60	0.488	0.899	0.211	0.329	0.603	0.553	0.547	1.010**	0.183
0.55	0.493	0.907	0.209	0.333	0.609	0.554	0.547	1.009**	0.182
0.50	0.498	0.916	0.207	0.341	0.624	0.558	0.548	1.011**	0.182
0.45	0.504	0.928	0.206	0.357	0.654	0.565	0.550	1.014**	0.181
0.40	0.509	0.938	0.204	0.368	0.673	0.570	0.551	1.016**	0.180
0.35	0.514	0.948	0.202	0.380	0.696	0.574	0.551	1.016**	0.179
0.30	0.520	0.958	0.200	0.401	0.735	0.581	0.552	1.018**	0.178
0.25	0.525	0.967	0.197	0.418	0.765	0.586	0.552	1.018**	0.176

Table 7.5: Utility of an arbitrary service provider assuming unilateral manipulation in $(2{,}2{,}\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			EFT-1			ETF-2		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
0.20	0.531	0.978	0.195	0.439	0.804	0.590	0.553	1.019**	0.175
0.15	0.536	0.987	0.191	0.464	0.849	0.592	0.553	1.019**	0.173
0.10	0.540	0.994	0.188	0.494	0.905	0.594	0.551	1.015**	0.172
0.05	0.542	0.998	0.186	0.516	0.944	0.594	0.547	1.009**	0.172
0.00	0.543	1.000	0.000	0.546	1.000	0.000	0.542	1.000	0.000
-0.05	0.542	0.998	0.184	0.577	1.057**	0.587	0.535	0.986	0.175
-0.10	0.539	0.992	0.185	0.599	1.096**	0.581	0.525	0.969	0.180
-0.15	0.532	0.981	0.188	0.635	1.162**	0.573	0.512	0.945	0.186
-0.20	0.523	0.963	0.194	0.666	1.219**	0.558	0.496	0.914	0.195
-0.25	0.513	0.946	0.200	0.687	1.256**	0.548	0.479	0.883	0.204
-0.30	0.502	0.924	0.206	0.700	1.282**	0.537	0.460	0.848	0.213
-0.35	0.489	0.901	0.213	0.717	1.312**	0.525	0.440	0.811	0.223
-0.40	0.477	0.879	0.219	0.728	1.332**	0.515	0.420	0.775	0.232
-0.45	0.461	0.850	0.227	0.740	1.353**	0.502	0.397	0.731	0.242
-0.50	0.448	0.826	0.234	0.745	1.364**	0.492	0.376	0.693	0.252
-0.55	0.433	0.797	0.240	0.754	1.379**	0.481	0.352	0.649	0.261
-0.60	0.418	0.771	0.247	0.754	1.379**	0.474	0.330	0.608	0.270
-0.65	0.407	0.750	0.253	0.755	1.381**	0.470	0.310	0.572	0.279
-0.70	0.393	0.724	0.258	0.752	1.376**	0.465	0.288	0.531	0.287
-0.75	0.379	0.699	0.263	0.752	1.377**	0.460	0.267	0.491	0.295
-0.80	0.366	0.674	0.268	0.751	1.374**	0.456	0.245	0.452	0.303
-0.85	0.353	0.650	0.272	0.749	1.370**	0.453	0.223	0.412	0.310
-0.90	0.337	0.621	0.278	0.740	1.354**	0.452	0.199	0.368	0.320
-0.95	0.323	0.594	0.283	0.734	1.343**	0.450	0.177	0.326	0.327

Configuration $(2{,}2{,}\alpha_3)$ represents a setting that induces very little competition due to the low number of service providers per candidate pool and the high α affecting the surplus to be distributed. The results show that, using ETF-1, undercutting down to $r = -0.95$ significantly increases v_j's utility. Generally, applying ETF-1, undercutting becomes a profitable strategy in configurations with a high surplus since losses incurred by being allocated with a price that is lower than the costs are likely to be overcompensated by a high absolute share in Δ. The ETF-2 gives rise to significant manipulation gains from overbidding up to $r = 0.8$. Rising prices do not affect the relative share in Δ, therefore overbidding is not effectively penalized. Both of these effects can generally be observed throughout all tested configurations (cp. Figure 7.4). The PRTF only allows, if at all, for profitable manipulation in an infinitesimal vicinity of $r = 0$ that cannot be captured by the simulation. Table 7.6 shows the simulation results for the configuration $(3{,}3{,}\alpha_1)$

Table 7.6: Utility of an arbitrary service provider assuming unilateral manipulation in $(3{,}3{,}\alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			EFT-1			ETF-2		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.005	0.772	0.019	0.005	0.782	0.025	0.006	0.922	0.018
0.95	0.005	0.795	0.020	0.005	0.807	0.026	0.006	0.944	0.018
0.90	0.005	0.805	0.020	0.005	0.815	0.026	0.006	0.952	0.019
0.85	0.005	0.820	0.020	0.005	0.825	0.026	0.006	0.964	0.019

Table 7.6: Utility of an arbitrary service provider assuming unilateral manipulation in $(3,3,\alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
0.80	0.005	0.819	0.020	0.005	0.820	0.026	0.006	0.963	0.018
0.75	0.005	0.831	0.020	0.005	0.829	0.026	0.006	0.972	0.018
0.70	0.005	0.849	0.020	0.005	0.855	0.027	0.006	0.985	0.018
0.65	0.005	0.870	0.021	0.005	0.875	0.027	0.006	1.004	0.019
0.60	0.005	0.875	0.020	0.005	0.877	0.027	0.006	1.001	0.018
0.55	0.005	0.895	0.021	0.005	0.894	0.027	0.006	1.017	0.019
0.50	0.006	0.901	0.021	0.005	0.892	0.027	0.006	1.018	0.019
0.45	0.006	0.914	0.021	0.005	0.914	0.027	0.006	1.029*	0.018
0.40	0.006	0.941	0.021	0.006	0.956	0.028	0.007	1.054**	0.019
0.35	0.006	0.967	0.021	0.006	0.978	0.028	0.007	1.072**	0.019
0.30	0.006	0.976	0.021	0.006	0.978	0.028	0.007	1.070**	0.019
0.25	0.006	0.983	0.021	0.006	0.984	0.028	0.007	1.074**	0.018
0.20	0.006	1.002	0.021	0.006	1.015	0.028	0.007	1.077**	0.018
0.15	0.006	1.012*	0.021	0.006	1.028*	0.028	0.007	1.079**	0.018
0.10	0.006	1.015**	0.021	0.006	1.026*	0.028	0.007	1.062**	0.017
0.05	0.006	1.012**	0.020	0.006	1.013*	0.027	0.006	1.037**	0.016
0.00	0.006	1.000	0.000	0.006	1.000	0.000	0.006	1.000	0.000
-0.05	0.006	0.962	0.020	0.006	1.003	0.027	0.006	0.938	0.016
-0.10	0.006	0.909	0.019	0.006	0.953	0.027	0.005	0.849	0.016
-0.15	0.005	0.789	0.021	0.005	0.831	0.027	0.004	0.693	0.018
-0.20	0.004	0.591	0.023	0.004	0.660	0.028	0.003	0.447	0.021
-0.25	0.002	0.350	0.027	0.002	0.389	0.032	0.001	0.154	0.027
-0.30	0.000	-0.012	0.034	0.000	0.022	0.037	-0.002	-0.273	0.035
-0.35	-0.003	-0.450	0.042	-0.003	-0.428	0.045	-0.005	-0.783	0.045
-0.40	-0.007	-1.110	0.053	-0.007	-1.113	0.055	-0.010	-1.533	0.057
-0.45	-0.012	-1.890	0.065	-0.011	-1.911	0.067	-0.015	-2.418	0.070
-0.50	-0.018	-2.962	0.080	-0.018	-3.037	0.081	-0.023	-3.604	0.086
-0.55	-0.026	-4.324	0.097	-0.027	-4.454	0.099	-0.032	-5.101	0.104
-0.60	-0.034	-5.583	0.111	-0.035	-5.765	0.113	-0.041	-6.517	0.120
-0.65	-0.045	-7.407	0.130	-0.046	-7.654	0.133	-0.053	-8.515	0.141
-0.70	-0.058	-9.444	0.149	-0.059	-9.768	0.152	-0.067	-10.757	0.161
-0.75	-0.071	-11.666	0.169	-0.072	-12.053	0.173	-0.082	-13.210	0.182
-0.80	-0.086	-14.126	0.188	-0.088	-14.627	0.192	-0.099	-15.933	0.203
-0.85	-0.102	-16.749	0.208	-0.104	-17.407	0.213	-0.118	-18.849	0.225
-0.90	-0.122	-19.897	0.229	-0.124	-20.683	0.235	-0.139	-22.321	0.249
-0.95	-0.144	-23.488	0.252	-0.147	-24.447	0.259	-0.164	-26.260	0.273

In this setting, deviation from truth-telling applying the PRTF is significantly beneficial up to a manipulation rate of $r = 0.15$, which equals the profitable deviation in case of the ETF-1. With respect to ETF-2, $r = 0.6$ still significantly improves service providers' utilities. Generally, as the data in Figure 7.4 shows, the PRTF performs evenly well in all settings with $|Y| = 2$.[12] In settings with $|Y| \in \{3,4\}$, a low and medium customer's willingness to pay abets increased manipulation (cp. Figure 7.4).[13] Table 7.7 exemplarily shows the simulation results for a setting with four

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[12] An exception is $(2,5,\alpha_3)$. Due to the high degree of competition as to the services' allocation, allocation probability decreases and, at the same time, the high level of α fosters an undercutting strategy resulting in a maximum profitable deviation of $r = -0.15$.

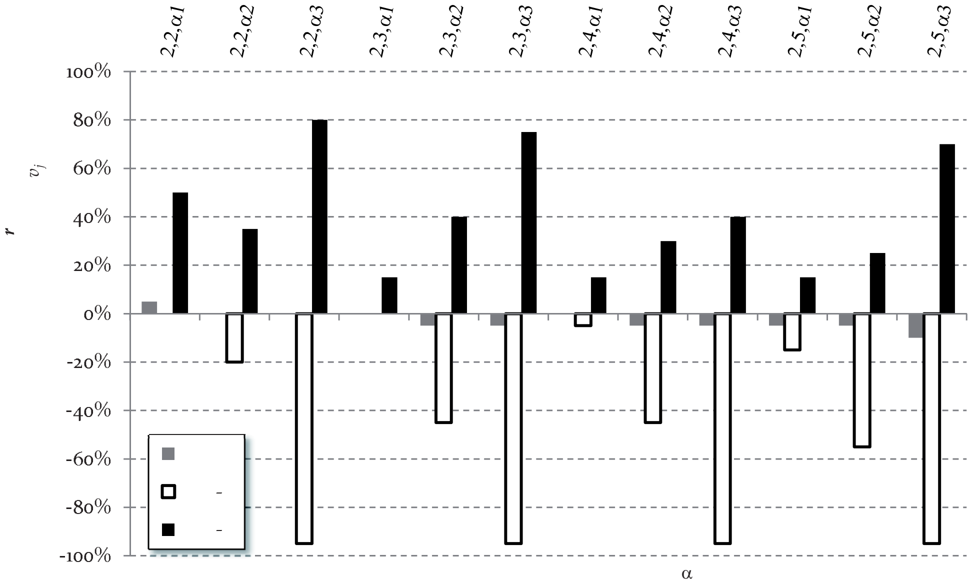
[13] Additional detailed simulation data is provided in Section B.2.1.

candidate pools $(4,2,\alpha_1)$, which increases the competition for receiving a share of Δ, while $|Y^k| = 2$ represents a rather high probability of allocation.

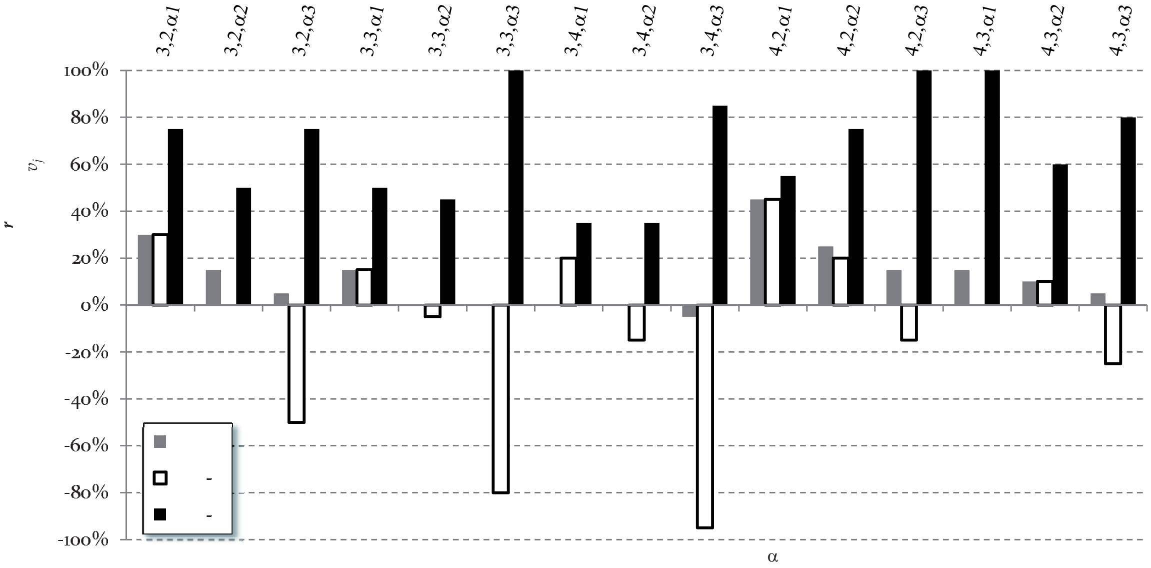
Table 7.7: Utility of an arbitrary service provider assuming unilateral manipulation in $(4,2,\alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.001	0.928	0.009	0.001	0.939	0.010	0.001	1.006	0.009
0.95	0.001	0.947	0.009	0.001	0.953	0.011	0.001	1.020	0.009
0.90	0.001	0.938	0.009	0.001	0.941	0.010	0.001	1.010	0.009
0.85	0.001	0.948	0.009	0.001	0.957	0.010	0.001	1.014	0.009
0.80	0.001	0.939	0.009	0.001	0.945	0.010	0.001	0.998	0.009
0.75	0.001	0.930	0.009	0.001	0.932	0.010	0.001	0.988	0.008
0.70	0.001	0.949	0.009	0.001	0.945	0.010	0.001	0.999	0.008
0.65	0.001	1.015	0.009	0.001	1.042	0.011	0.001	1.055	0.009
0.60	0.001	1.028	0.009	0.001	1.056	0.011	0.001	1.060	0.009
0.55	0.001	1.043	0.009	0.001	1.065	0.011	0.001	1.076*	0.009
0.50	0.001	1.026	0.009	0.001	1.043	0.011	0.001	1.094**	0.009
0.45	0.001	1.087*	0.010	0.001	1.096*	0.011	0.001	1.105**	0.009
0.40	0.001	1.159**	0.010	0.001	1.170**	0.012	0.001	1.162**	0.010
0.35	0.001	1.145**	0.010	0.001	1.149**	0.012	0.001	1.160**	0.010
0.30	0.001	1.118**	0.010	0.001	1.116*	0.011	0.001	1.140**	0.009
0.25	0.001	1.143**	0.009	0.001	1.132**	0.011	0.001	1.152**	0.009
0.20	0.001	1.166**	0.009	0.001	1.169**	0.011	0.001	1.164**	0.009
0.15	0.001	1.150**	0.009	0.001	1.143**	0.011	0.001	1.149**	0.008
0.10	0.001	1.131**	0.008	0.001	1.136**	0.010	0.001	1.136**	0.008
0.05	0.001	1.075**	0.008	0.001	1.079**	0.010	0.001	1.078**	0.007
0.00	0.001	1.000	0.000	0.001	1.000	0.000	0.001	1.000	0.000
-0.05	0.001	0.905	0.007	0.001	0.904	0.009	0.001	0.907	0.007
-0.10	0.001	0.765	0.007	0.001	0.773	0.009	0.001	0.757	0.007
-0.15	0.001	0.554	0.008	0.001	0.560	0.009	0.001	0.541	0.007
-0.20	0.000	0.292	0.009	0.000	0.295	0.010	0.000	0.268	0.009
-0.25	0.000	-0.079	0.012	0.000	-0.056	0.012	0.000	-0.108	0.012
-0.30	-0.001	-0.490	0.014	-0.001	-0.420	0.014	-0.001	-0.529	0.014
-0.35	-0.002	-1.395	0.020	-0.001	-1.221	0.020	-0.002	-1.412	0.020
-0.40	-0.003	-2.212	0.024	-0.002	-1.988	0.024	-0.003	-2.233	0.025
-0.45	-0.004	-3.510	0.032	-0.004	-3.257	0.032	-0.004	-3.521	0.033
-0.50	-0.006	-4.906	0.039	-0.006	-4.595	0.039	-0.006	-4.897	0.040
-0.55	-0.008	-7.113	0.049	-0.008	-6.650	0.049	-0.009	-7.048	0.051
-0.60	-0.011	-9.191	0.059	-0.010	-8.628	0.059	-0.011	-9.087	0.060
-0.65	-0.013	-11.678	0.069	-0.013	-11.006	0.070	-0.014	-11.553	0.072
-0.70	-0.017	-14.727	0.080	-0.017	-13.942	0.081	-0.018	-14.558	0.083
-0.75	-0.021	-18.374	0.094	-0.021	-17.494	0.095	-0.022	-18.138	0.097
-0.80	-0.026	-22.372	0.107	-0.026	-21.375	0.108	-0.027	-22.073	0.111
-0.85	-0.032	-28.214	0.125	-0.033	-27.008	0.126	-0.034	-27.765	0.129
-0.90	-0.038	-33.182	0.139	-0.038	-31.757	0.140	-0.040	-32.667	0.144
-0.95	-0.047	-40.995	0.159	-0.048	-39.328	0.161	-0.050	-40.255	0.165

In the case of $(4,2,\alpha_1)$, the PRTF allows for increased profitable manipulation up to $r = 0.45$. The purely competitive benchmark ETF-1 does not perform better, also allowing for profitable deviation of $r = 0.45$. In case of the ETF-2, a manipulation rate up to $r = 0.55$ increases the utility of an average service provider. To summarize, in Figure 7.4 the manipulation rates that significantly improve a service provider's utility are depicted for all tested configurations.



(a) Network configurations with $|Y| = 2$

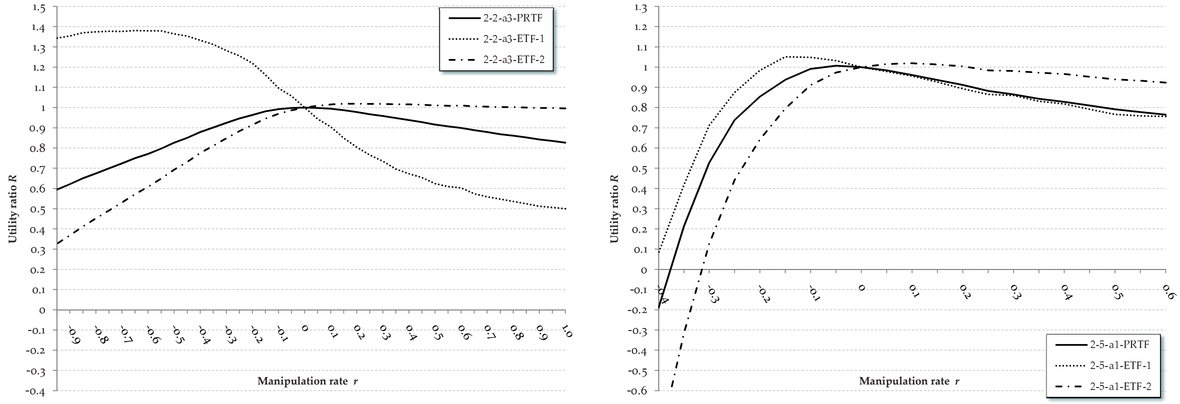


(b) Network configurations with $|Y| \in \{3,4\}$

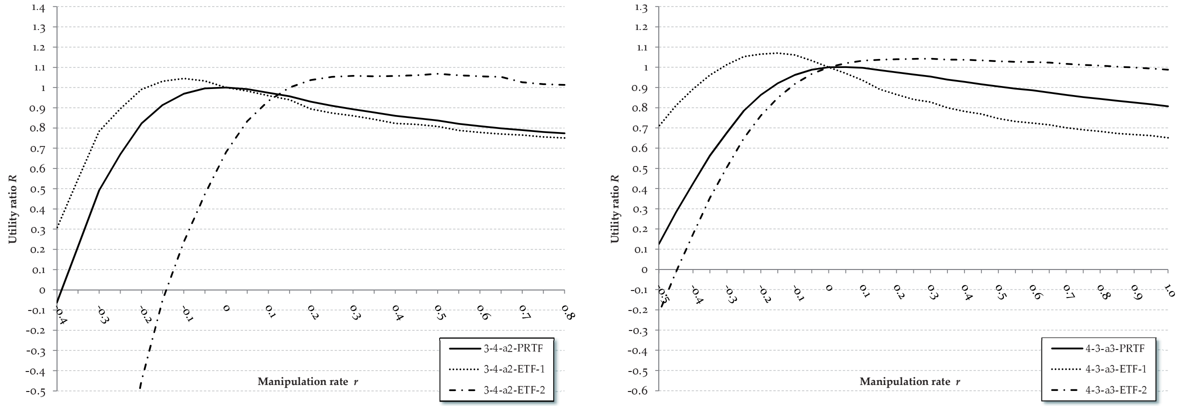
Figure 7.4: Manipulation rates which significantly increase a service provider's utility assuming unilateral deviation

It is not only interesting to evaluate the maximum manipulation rate that significantly increases the utility of service providers, but also the manipulation rate that maximizes the profit ratio. In Figure 7.5 the relative utility gain (or loss) from manipulation by x% subject to any other service provider reporting its true type is plotted for selected configurations in which the PRTF does not allow for profitable deviation of more than $r = |0.05|$. Figure 7.6 shows exemplary configurations in which the PRTF is prone to more severe beneficial manipulation of a single service provider.

An illustration of manipulation rates that *maximize* the service providers' utilities in different configurations analogue to Figure 7.4 can be found in Section B.2.1 (cp. Figure B.1). Moreover, detailed simulation data in tabular form for additional network configurations that were not shown in Tables 7.5 to 7.7 can be found in Tables B.3 to B.10; an illustration of their relative utility gain is plotted in Figures B.2 and B.3.

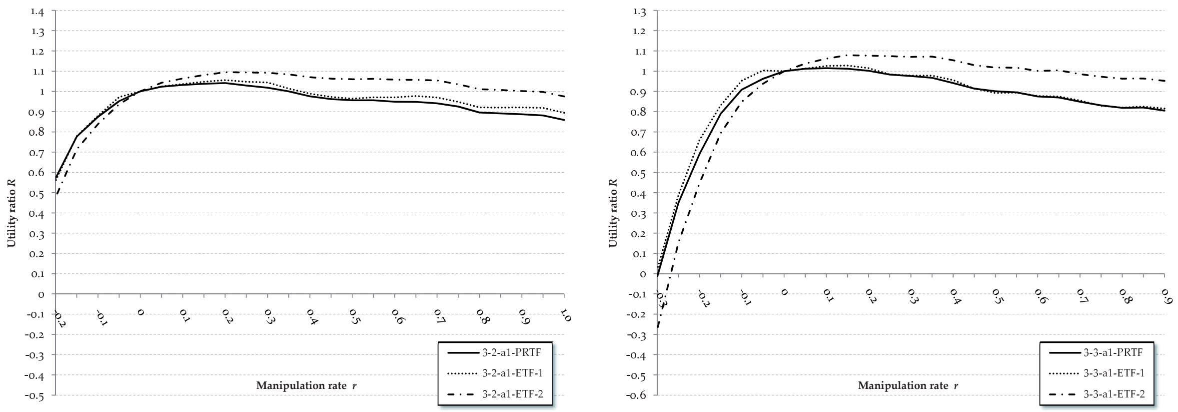


(a) Utility ratios in $(2,2,\alpha_3)$ **(b)** Utility ratios in $(2,5,\alpha_1)$



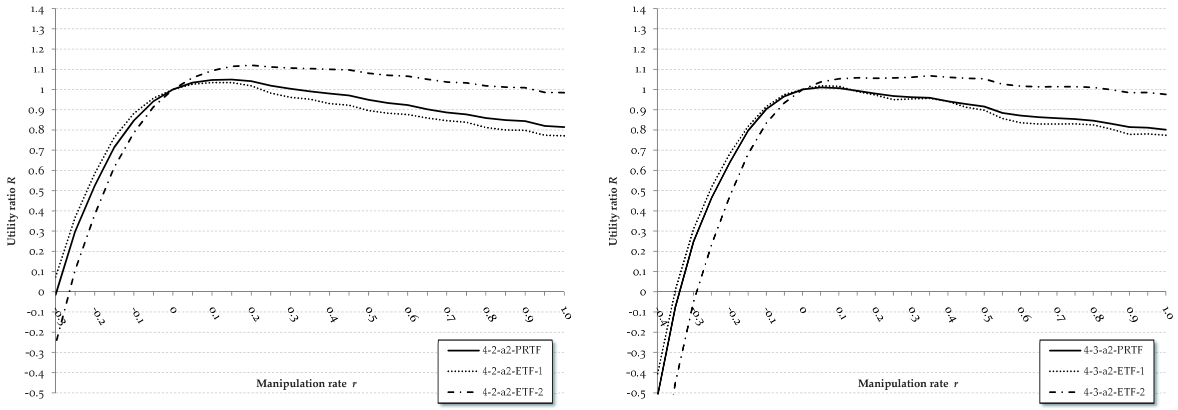
(c) Utility ratios in $(3,4,\alpha_2)$ **(d)** Utility ratios in $(4,3,\alpha_3)$

Figure 7.5: Utility ratios of different manipulation rates applying unilateral strategies (selected configurations): The PRTF only allows for profitable deviation in a negligible range



(a) Utility ratios in $(3,2,\alpha_1)$

(b) Utility ratios in $(3,3,\alpha_1)$



(c) Utility ratios in $(4,2,\alpha_2)$

(d) Utility ratios in $(4,3,\alpha_2)$

Figure 7.6: Utility ratios of different manipulation rates applying unilateral strategies (selected configurations): The PRTF allows for more severe profitable deviation

Summary

The simulation data shows the peculiarities of the three transfer functions in the scenario that assumes unilateral deviation of one service provider subject to all others revealing their true type. The observations made above are summarized in the following.

- The PRTF turns out to be quite balanced over all configurations. A small number of candidate pools ($|Y^k| = 2$ and $|Y^k| = 3$) generally favors truthful revelation. Only $(2,5,\alpha_3)$ allows for intermediate manipulation due to *(i)* the quite high competition for allocation and *(ii)* the high Δ. The former decreases the probability of allocation, which provokes a higher tendency to an undercutting strategy. This effect is strengthened by the high willingness to pay which can potentially overcompensate losses from undercutting and being allocated (cp. also ETF-1). Quite the contrary applies for $(3,2,\alpha_1)$, $(3,2,\alpha_2)$, and $(3,3,\alpha_1)$: service providers tend to overstate their costs due to the low competition for being allocated. In the configurations $(3,3,\alpha_3)$ and $(3,4,\alpha_i)$, $i \in \{1,2,3\}$, the undercutting effect is mitigated by the competition that both evolves from more candidate pools and a high number of services therein. In configurations with

$|Y| = 4$, intermediate overstating is advantageous – the higher allocation probability seems to overcompensate decreasing power ratios.

- Particularly in settings with a high willingness to pay of the customer, the ETF-1 is prone to severe undercutting as discussed above. In this case, the distributed Δ has a very strong impact since it is only granted to $|Y|$ service providers. Therefore, service providers want to be allocated and accept losses through undercutting in return for the profits from participating in Δ. If the probability of allocation is higher and, at the same time, α is lower, a reversed effect can be observed. In configurations with a low number of services, manipulation does not pay off in general. With a rising number of candidate pools, intermediate overstating becomes profitable for the same reason than in the PRTF case.

- The ETF-2 always distributes Δ equally to all services in each of the candidate pools. Obviously, service providers never have an incentive to undercut their costs. Such an action would not change their share in Δ. Vice versa, overstating the true costs is always favorable since, if allocated, profits can be made. The level of upwards variations heavily depends on the network configuration.

In summary, Figure 7.4 gives a first indication that *the PRTF performs better than the ETF-2 in every of the tested configuration*. Moreover, the PRTF outperforms the ETF-1 in several configurations, particularly in settings with a high willingness to pay of the customer.

Solely scrutinizing unilateral bidding strategies does, however, not suffice to make founded statements on the manipulation robustness of the co-opetition mechanism. Therefore, the following section analyzes a situation in which all agents simultaneously manipulate their bids by x%.

7.1.2.3 Symmetric Strategies

Simulation Model

In a second simulation model, the simulation described in Section 7.1.2.2 is exactly reproduced except for the service providers' manipulation strategies. While the former setting simulates unilateral deviation from truth-telling with all other agents revealing their true costs, the current simulation model assumes symmetric manipulation strategies r_{sym}. In other words, if the considered service provider manipulates prices by x%, every other agent also chooses to deviate by x% from its true valuation [260]. Therefore, the updated utility ratio $R_j^{r_{sym}}$ for an arbitrary service provider $v_j \in V$ assembles as follows:

$$R_j^{r_{sym}} = \frac{u_j^{r_{sym}}}{u_j^{truth}} \tag{7.11}$$

Accordingly, the applied one-tailed matched-pairs t-test analyzes the following hypothesis: *Service providers benefit from manipulation at manipulation rate r while all* *other agents also manipulate by r*. That is, $u_j^{r_{sym}} - u_j^{truth} > 0 \Rightarrow R_j^{r_{sym}} > 1$ must be significant.

Simulation Results

Other than when applying unilateral strategies, symmetric deviation is in average, if at all, only significant in a very close range to $r = 0$ subject to the tested configurations. This is true for the PRTF and for both benchmarks. This behavior is exemplarily illustrated via two characteristic configurations, $(3{,}2{,}\alpha_1)$ and $(3{,}3{,}\alpha_3)$.

In configurations with a small α, symmetric deviation quite rapidly leads to a decreasing utility ratio in either direction as shown in Table 7.8. Again, for each payment rule and at each manipulation level r, the mean absolute utilities $u_j^{r_{sym}}$ (AU), the mean utility ratio $R_j^{r_{sym}}$ (UR) of a service provider with all others also manipulating by r, and the standard deviation (SD) of the mean absolute utility are outlined.

Table 7.8: Utility of an arbitrary service provider assuming symmetric manipulation in $(3{,}2{,}\alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.002	0.305	0.019	0.002	0.319	0.020	0.002	0.300	0.018
0.95	0.002	0.364	0.021	0.002	0.377	0.022	0.002	0.357	0.020
0.90	0.002	0.401	0.022	0.002	0.415	0.022	0.002	0.395	0.021
0.85	0.002	0.407	0.021	0.002	0.420	0.022	0.002	0.405	0.021
0.80	0.002	0.443	0.022	0.002	0.454	0.023	0.002	0.438	0.021
0.75	0.002	0.460	0.022	0.002	0.469	0.023	0.002	0.454	0.021
0.70	0.003	0.485	0.022	0.003	0.493	0.023	0.003	0.483	0.021
0.65	0.003	0.504	0.022	0.003	0.511	0.023	0.003	0.503	0.021
0.60	0.003	0.516	0.022	0.003	0.522	0.023	0.003	0.520	0.020
0.55	0.003	0.564	0.022	0.003	0.569	0.023	0.003	0.568	0.020
0.50	0.003	0.593	0.022	0.003	0.597	0.023	0.003	0.593	0.020
0.45	0.003	0.631	0.022	0.003	0.635	0.024	0.003	0.625	0.020
0.40	0.004	0.676	0.023	0.004	0.681	0.024	0.004	0.663	0.020
0.35	0.004	0.701	0.022	0.004	0.705	0.024	0.004	0.696	0.020
0.30	0.004	0.747	0.022	0.004	0.750	0.024	0.004	0.740	0.020
0.25	0.004	0.807	0.023	0.004	0.810	0.024	0.004	0.787	0.020
0.20	0.005	0.875	0.023	0.005	0.878	0.025	0.005	0.850	0.020
0.15	0.005	0.926	0.023	0.005	0.927	0.025	0.005	0.897	0.020
0.10	0.005	0.964	0.022	0.005	0.965	0.025	0.005	0.952	0.019
0.05	0.005	0.989	0.022	0.005	0.988	0.024	0.005	0.974	0.018
0.00	0.005	1.000	0.000	0.005	1.000	0.000	0.005	1.000	0.000
-0.05	0.005	0.985	0.021	0.005	0.985	0.024	0.005	0.998	0.018
-0.10	0.005	0.935	0.021	0.005	0.931	0.025	0.005	0.938	0.019
-0.15	0.004	0.815	0.023	0.004	0.807	0.027	0.004	0.812	0.021
-0.20	0.003	0.646	0.026	0.003	0.636	0.029	0.003	0.640	0.026
-0.25	0.002	0.318	0.032	0.002	0.303	0.034	0.002	0.327	0.033
-0.30	-0.001	-0.115	0.039	-0.001	-0.136	0.041	-0.001	-0.106	0.041
-0.35	-0.005	-1.032	0.053	-0.006	-1.065	0.053	-0.005	-1.002	0.055
-0.40	-0.011	-2.056	0.067	-0.011	-2.105	0.066	-0.011	-2.001	0.071
-0.45	-0.018	-3.320	0.083	-0.018	-3.384	0.079	-0.018	-3.260	0.088
-0.50	-0.028	-5.340	0.104	-0.029	-5.437	0.098	-0.028	-5.258	0.109
-0.55	-0.041	-7.653	0.126	-0.041	-7.790	0.117	-0.041	-7.569	0.132
-0.60	-0.054	-10.191	0.149	-0.055	-10.365	0.136	-0.054	-10.086	0.155

Table 7.8: Utility of an arbitrary service provider assuming symmetric manipulation in $(3,2,\alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
-0.65	-0.068	-12.748	0.172	-0.069	-12.966	0.155	-0.068	-12.633	0.179
-0.70	-0.076	-14.273	0.191	-0.077	-14.532	0.168	-0.076	-14.152	0.198
-0.75	-0.082	-15.465	0.210	-0.084	-15.771	0.179	-0.082	-15.329	0.216
-0.80	-0.085	-15.853	0.226	-0.086	-16.203	0.187	-0.084	-15.717	0.231
-0.85	-0.084	-15.837	0.240	-0.086	-16.227	0.192	-0.084	-15.703	0.244
-0.90	-0.084	-15.821	0.254	-0.086	-16.250	0.197	-0.084	-15.689	0.257
-0.95	-0.084	-15.805	0.269	-0.086	-16.274	0.202	-0.084	-15.676	0.270

In case of a higher α, losses from overstating or undercutting true valuations become smaller. In some configurations, manipulation in both directions yields approximately the same utility ratio than truth-telling. Yet, deviation does not significantly increase the service providers' utilities: stating a price in close proximity to $r = 0$ is still an at least weakly dominant strategy. Table 7.9 exemplarily shows this behavior for $(3,3,\alpha_3)$.

Table 7.9: Utility of an arbitrary service provider assuming symmetric manipulation in $(3,3,\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

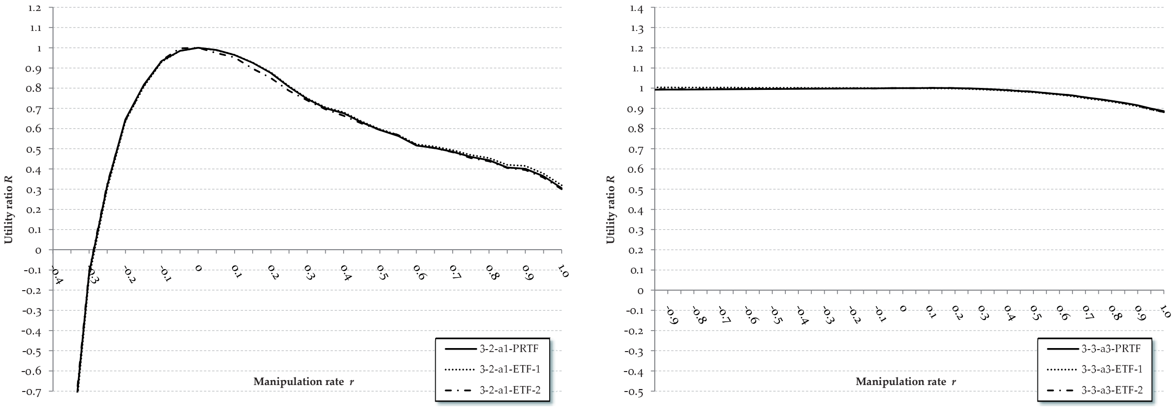
	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.189	0.886	0.254	0.191	0.881	0.349	0.188	0.882	0.215
0.95	0.192	0.899	0.247	0.194	0.894	0.348	0.191	0.895	0.209
0.90	0.195	0.915	0.241	0.198	0.910	0.348	0.195	0.913	0.203
0.85	0.198	0.927	0.235	0.200	0.922	0.347	0.197	0.925	0.195
0.80	0.200	0.937	0.227	0.203	0.933	0.345	0.200	0.937	0.187
0.75	0.202	0.946	0.219	0.204	0.942	0.344	0.202	0.946	0.180
0.70	0.204	0.954	0.211	0.206	0.950	0.343	0.203	0.954	0.171
0.65	0.206	0.964	0.202	0.208	0.960	0.342	0.205	0.964	0.163
0.60	0.207	0.970	0.193	0.210	0.967	0.340	0.207	0.970	0.155
0.55	0.209	0.976	0.184	0.211	0.973	0.339	0.208	0.976	0.146
0.50	0.210	0.982	0.174	0.213	0.979	0.338	0.209	0.982	0.137
0.45	0.211	0.986	0.165	0.213	0.983	0.337	0.210	0.987	0.128
0.40	0.212	0.990	0.155	0.214	0.987	0.336	0.211	0.991	0.120
0.35	0.212	0.994	0.146	0.215	0.991	0.335	0.212	0.994	0.112
0.30	0.213	0.997	0.136	0.216	0.994	0.334	0.212	0.996	0.104
0.25	0.213	0.999	0.127	0.216	0.996	0.333	0.213	0.999	0.096
0.20	0.214	1.000	0.118	0.217	0.998	0.333	0.213	1.000	0.090
0.15	0.214	1.001	0.110	0.217	0.999	0.332	0.213	1.001	0.085
0.10	0.214	1.001	0.103	0.217	0.999	0.332	0.213	1.001	0.081
0.05	0.214	1.000	0.097	0.217	1.000	0.332	0.213	1.000	0.079
0.00	0.214	1.000	0.000	0.217	1.000	0.000	0.213	1.000	0.000
-0.05	0.214	1.000	0.089	0.217	1.000	0.332	0.213	1.000	0.079
-0.10	0.213	0.999	0.088	0.217	1.000	0.333	0.213	0.999	0.082
-0.15	0.213	0.999	0.088	0.217	1.001	0.333	0.213	0.999	0.086
-0.20	0.213	0.998	0.090	0.217	1.001	0.334	0.213	0.999	0.091
-0.25	0.213	0.998	0.094	0.217	1.001	0.335	0.213	0.998	0.097
-0.30	0.213	0.998	0.099	0.217	1.001	0.335	0.213	0.998	0.104
-0.35	0.213	0.997	0.106	0.217	1.001	0.336	0.213	0.998	0.112
-0.40	0.213	0.997	0.113	0.217	1.002	0.337	0.213	0.998	0.121
-0.45	0.213	0.996	0.122	0.217	1.002	0.339	0.213	0.997	0.129

Table 7.9: Utility of an arbitrary service provider assuming symmetric manipulation in $(3,3,\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
-0.50	0.213	0.996	0.131	0.217	1.002	0.340	0.213	0.997	0.139
-0.55	0.213	0.996	0.140	0.218	1.002	0.342	0.212	0.997	0.148
-0.60	0.213	0.995	0.151	0.218	1.002	0.343	0.212	0.996	0.158
-0.65	0.212	0.995	0.161	0.218	1.003	0.345	0.212	0.996	0.168
-0.70	0.212	0.994	0.172	0.218	1.003	0.347	0.212	0.996	0.178
-0.75	0.212	0.994	0.183	0.218	1.003	0.349	0.212	0.995	0.188
-0.80	0.212	0.993	0.194	0.218	1.003	0.351	0.212	0.995	0.198
-0.85	0.212	0.993	0.206	0.218	1.003	0.353	0.212	0.995	0.209
-0.90	0.212	0.993	0.217	0.218	1.004	0.355	0.212	0.995	0.219
-0.95	0.212	0.992	0.229	0.218	1.004	0.358	0.212	0.994	0.230

The differences between configurations with a low Δ and configurations where a high surplus is distributed can be explained as follows: in contrast to unilateral deviation, symmetric deviation by $x\%$ *impacts the overall result much more severely due to the fact that all providers manipulate*. On the one hand, overstating bears the risk of a reduction of paths due to resulting prices that lie above the customer's willingness to pay – leading to no allocation at all in the worst case. On the other hand, by symmetric undercutting, new paths that were originally too expensive also "pretend to" create a positive value for the system since the impact on the overall price is much higher if each and every price is decreased than in the unilateral case. In this case, due to the low Δ, allocated services are likely to considerably lose from t^1 (cp. also Figure 7.1). In case of a high Δ, both undercutting and overstating do not change the service providers' utilities since above-described risks are hindered by the high customer's willingness to pay.

This behavior is illustrated in more detail in Figure 7.7, showing the trend of the utility ratios with changing manipulation rates for $(3,2,\alpha_1)$ and $(3,3,\alpha_3)$.



(a) Utility ratios in $(3,2,\alpha_1)$ **(b)** Utility ratios in $(3,3,\alpha_3)$

Figure 7.7: Utility ratios of different manipulation rates applying symmetric strategies (selected scenarios) (1)

A continuing analysis of symmetric bidding strategies will be provided in Section 7.1.2.4. In addition, a set of another four configurations is exemplarily illustrated via tables (cp. Tables B.11 to B.14) and diagrams (cp. Figure B.4) in Section B.2.2 in order to back up the statements on symmetric manipulation made in this section.

7.1.2.4 Implications and Further Analysis

The results of the simulation considering unilateral deviation of single service providers show that in the tested scenarios with two candidate pools, a variable number of services, and different levels of α, the PRTF does, in average, not allow for a profitable deviation of more than 5% (except for $(2{,}5{,}\alpha_3)$). In conjunction with the simulation results assuming symmetric deviation that yield the same results, it can be stated that misreporting their true valuation is not beneficial to service providers in these configurations. Consequently, as reported types and true types are likely to approximately coincide, the mechanism also exhibits a high degree of allocative efficiency at provider-side for configurations $(2{,}|Y^k|{,}\alpha_i)$, except for $(2{,}5{,}\alpha_3)$ (cp. Figure 7.4a).

A similar implication can generally be stated for several other configurations: In $(3{,}2{,}\alpha_3)$, $(3{,}3{,}\alpha_2)$, $(3{,}3{,}\alpha_3)$, $(3{,}4{,}\alpha_i)$ with $i \in \{1{,}2{,}3\}$, and $(4{,}3{,}\alpha_3)$, service providers cannot significantly improve their utility when deviating from their true type by more than 5%, both in case of unilateral and symmetric strategies.

Although the co-opetition mechanism is not incentive compatible in an analytical sense and counterexamples can be constructed as shown in Section 7.1.1, strategic behavior of service providers is substantially reduced and thus, the co-opetition mechanism exhibits a high manipulation robustness averaged over all service providers. This statements holds true for the above-named network configurations. In all of these cases, the co-opetition mechanism is also likely to be able to reach a high degree of allocative efficiency since, as shown in Section 7.1.1.2, truth-telling also implicates the allocative efficient outcome.

For the other configurations that were not mentioned in the previous paragraph (cp. also Table 7.11), service providers can increase their utility by unilateral deviation moderately to intensely, however, symmetric deviation does only allow for deviations in a negligible range. In respect of the PRTF,founded statements on equilibrium strategies cannot be made: if all service providers apply symmetric strategies, truth-telling would maximize the expected utility. However, if there is no other agent to deviate, unilateral deviation from the true type would again be beneficial.

A detailed consideration of symmetric strategies

Let us first have a closer look at the strategies in case of symmetric deviation. Again assume that F^{*truth} is allocated if every service provider reveals its true type. In case of symmetric deviation, the allocated path remains unchanged as long as an allocation is possible.[14] In total, $\mathcal{W}^{truth}$ remains unchanged, however, transfers are redistributed. Further assume a minimally intermeshed SVN configuration with

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[14] Yet, if all service providers increase their price, the system can run into a situation in which $\alpha > \mathcal{P}_{F_l}$, and thus, the allocation function does not pick any complex service.

strictly disjunctive paths (cp e.g. Figure 7.2).[15] In other words, each service is only located on one single path. Gains and losses evolve as follows:

1. Assume symmetric deviation by $r_{sym} = x,\ x > 0$, that is, increasing prices. As long as a complex service is generally allocated, allocated service providers are better off than in a symmetric truth-telling situation: let again ζ_j^{truth} denote service v_j's relative PR share in Δ^{truth}. As every service provider deviates in relative terms, services on the non-allocated paths are getting more expensive in absolute terms than the allocated services, which affects their power ratios. Therefore, for a service $v_h \notin W^*$, $\zeta_h^x < \zeta_h^{truth}$. Vice versa, the allocated services' relative shares in the PR-based payment rise subject to symmetric deviation. By playing $r_{sym} = x$, allocated services withdraw $x \cdot \sum_{v_j \in W^*} c_{ij}$ from the PR-based surplus compared to truth-telling, resulting in $\Delta' = \Delta^{truth} - x \cdot \sum_{e_{ij} \in E(W^*)} c_{ij}$ with $\Delta' < \Delta^{truth}$. Since $x \cdot \sum_{e_{ij} \in E(W^*)} c_{ij}$ is exclusively taken by the allocated services, for each allocated v_j the following equation holds:

   $$\zeta_j^x \cdot \Delta' > \zeta_j^{truth} \cdot \Delta^{truth} \tag{7.12}$$

   Therefore, compared to truth-telling, allocated services gain from a symmetric price increase while non-allocated services lose.

2. Analogously, assume symmetric deviation by $r_{sym} = -x,\ 0 < x < 1$, that is, decreasing prices. In this case, services on the non-allocated paths are getting cheaper than the allocated services in absolute terms, affecting the PR in the opposite direction than above: $\zeta_h^{-x} > \zeta_h^{truth}\ \forall\ v_h \notin W^*$. Vice versa, the allocated services' relative shares in the PR-based payment decrease. Playing $r_{sym} = -x$, allocated services lose $x \cdot \sum_{v_j \in W^*} c_{ij}$ as they undercut their actual costs. The PR-based surplus increases to $\Delta'' = \Delta^{truth} + x \cdot \sum_{e_{ij} \in E(W^*)} c_{ij}$ with $\Delta'' > \Delta^{truth}$. Since Δ'', which also includes the losses incurred by allocated services, is distributed amongst *all* services, for each allocated v_j the following equation holds:

   $$\zeta_j^{-x} \cdot \Delta'' < \zeta_j^{truth} \cdot \Delta^{truth} \tag{7.13}$$

   Therefore, compared to truth-telling, allocated services lose from a symmetric price decrease while non-allocated services gain.

Recall that this analysis is only valid for SVNs with disjunct paths. If, for instance, a service v_j is located at the best path and on several other paths exhibiting higher costs, symmetrically decreasing costs can be beneficial if the decrease in utility via the allocated edge is overcompensated by the increasing utility endowed by non-allocated edges.

Thus, in order to review if the analytic result for disjunctive paths can be generalized to any set F, the following simulation is conducted: for a distinct manipulation rate $r_{sym} \in \{-0.95, -0.5, -0.1, 0.1, 0.5, 1.0\}$, 10,000 rounds are simulated where

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[15] This situation is not a stable state as shown in Section 6.3 and and thus, technically, also excluded from the simulation setting (cp. Section 7.1.2.3). However, this easy-to-comprehed SVN helps to illustrate dependencies in a simplified manner.

in each of these rounds *(i)* a topology $(|Y|, |Y^k|, \alpha)$ with density $d = 1.0$ out of the set presented in Table 7.4 and *(ii)* a customer's willingness to pay $\alpha \in [0.5 \cdot |Y|; 4.0 \cdot |Y|]$ are randomly drawn. In each round, a service v_j that is allocated in a truth-telling scenario is randomly picked. Then, the chosen manipulation rate $r_{sym} = x$ is applied and the utilities u_j^{truth} and u_j^x are computed.

For each of the applied manipulation rates, the aggregated data is tested via a one-tailed matched-pairs t-test. For $r < 0$, the test analyzes the alternative hypothesis stated as follows: *Allocated service providers suffer from manipulation at manipulation rate r while all other service providers also manipulate by r.* Vice versa, for $r > 0$, the test analyzes the following alternative hypothesis: *Allocated service providers benefit from manipulation at manipulation rate r while all other service providers also manipulate by r.* Table 7.10 shows the aggregated simulation results.

Table 7.10: Logic of gains and losses applying symmetric bidding strategies "Avg of" denotes the average of the sum over all 10,000 data points, both for truth-telling and $r_{sym} = x$. * denotes significance at the level $p = 0.01$.

$r_{sym} = x$	Avg of u_j^{truth}	Avg of u_j^x
-0.95	0.110*	-0.146
-0.5	0.105*	-0.024
-0.1	1.110*	1.089
0.1	1.112	1.125*
0.5	1.111	1.125*
1.0	1.104	1.086

The null hypotheses can be rejected in each simulation except for $r_{sym} = 1.0$. An analysis of the simulation data shows that, in this extreme case, deviating leads to no allocation at all in the bulk of rounds which definitely sets $u_j^{1.0} = 0 < u_j^{truth}$. However, generally one can state that, if overstating the true costs does not lead to a situation where there is no path to be allocated, the results from the analysis of disjunctive paths can be generalized to any set of F, given the network configurations at hand (cp. Table 7.4).

To summarize, applying symmetric strategies, the service providers' interests are conflicting depending on them being allocated or not. This conflict can be consulted as an explanation for the results of the symmetric manipulation simulations. On average, the service providers' strategies seem to cancel out, leading to the results presented in Section 7.1.2.3.

Service providers' strategies modeled as a game in strategic form

The insights gained from the preceding paragraph can be applied to a more general setting, abandoning symmetric strategies. Either interest group (allocated and non-allocated service providers) risks to switch its group: previously non-allocated services are more likely to be allocated when decreasing the price and allocated services are prone to fall off the best path through a price increase. Certainly, such a switch would in turn bring about a switch in the optimal bidding strategy. In the following, based on the results provided in Sections 7.1.2.2 and 7.1.2.3, individual bidding strategies are analyzed by dint of a simplified game in strategic form considering two (average) agents (cp. Figure 7.8).

As outlined in Section 7.1.2.3, there is a strong indication that the utility ratio A of symmetric deviation is smaller than the utility ratio 1 of truth-telling if the customer's willingness to pay is rather small, thus resulting in $A < 1$. From Section 7.1.2.2, we know that unilateral deviation can be beneficial in several configurations, which is also assumed in this analysis. Therefore, $B > 1$ holds. From $B > 1$ it follows that $C < 1$.

		Service provider 2	
		deviate	truth
Service provider 1	deviate	A,A	B,C
	truth	C,B	1,1

Figure 7.8: Service providers' bidding strategies as a simplified two-agent strategic form game

In order to determine the pure strategy Nash equilibria of the game depicted in Figure 7.8, three different cases must be distinguished given the assumptions made above.

1. $A > C$: The utility ratio A of an agent in case of symmetric deviation is higher than the utility ratio C if playing truth-telling and the other agent playing deviate. Thus, the pure strategy Nash equilibrium is *(deviate,deviate)*. *(deviate,deviate)* is a Nash equilibrium although it is not pareto optimal: both agents could improve their utilities by playing *(truth,truth)*. Therefore, if $A > C$, the game is an instance of the prisoner's dilemma [215].
2. $A < C$: The utility ratio A of an agent in case of symmetric deviation is less than the utility ratio C if playing truth-telling and the other agent playing deviate. Thus, there are two pure strategy Nash equilibria: *(deviate,truth)* and *(truth,deviate)*.
3. $A = C$: The utility ratio A of an agent in case of symmetric deviation equals the utility ratio C if playing truth-telling and the other agent playing deviate. Thus, there are three pure strategy Nash equilibria: *(deviate,deviate)*, *(deviate,truth)* and *(truth,deviate)*.

In total, the strategic form game depicted in Figure 7.8 shows that a final statement on manipulation robustness, and thus, on the co-opetition mechanism's degree of allocative efficiency, cannot be made solely based on unilateral and symmetric bidding strategies.

Summary

As listed in Table 7.11, applying the PRTF, several network configurations only allow for manipulation rates in a negligible range of $r_{uni} \leq |0.05|$ considering individual services. At the same time, these scenarios do not allow for profitable deviation if all participating service providers in the SVN manipulate their bids symmetrically. In more detail, regarding these network configurations, applying *unilateral bidding strategies*, the PRTF allows for an average of $|r|^{\text{PRTF}}_{\varnothing,uni} = 0.028$, whereas the ETF-2 allows for a profitable average manipulation rate of $|r|^{\text{ETF-2}}_{\varnothing,uni} = 0.486$. Significance to a level of 1% can be stated via a Wilcoxon signed-rank test.[16] The second simulation setting testing symmetric manipulation generally found that this kind of deviation is profitable under none of the applied transfer functions, resulting in $|r|^{\text{PRTF}}_{\varnothing,sym} = |r|^{\text{ETF-2}}_{\varnothing,sym} = 0$ for each tested topology. Obviously, since the data of the second simulation literally cancels out, it can be stated that the PRTF is more robust against manipulation than the ETF-2, and therefore, Hypothesis 7.1 holds for the network configurations outlined in the first row of Table 7.11

In order to analyze bidding strategies for the configurations that did not yield clear results in Sections 7.1.2.2 and 7.1.2.3, individual, yet simultaneous bidding strategies need to be considered (cp. Section 7.1.3).

Table 7.11: Network configurations and their manipulation robustness: Intermediate results

r	Network configurations
$r \leq \|0.05\|$	$(2,2,\alpha_1)$, $(2,2,\alpha_2)$, $(2,2,\alpha_3)$, $(2,3,\alpha_1)$, $(2,3,\alpha_2)$, $(2,3,\alpha_3)$, $(2,4,\alpha_1)$, $(2,4,\alpha_2)$, $(2,4,\alpha_3)$, $(2,5,\alpha_1)$, $(2,5,\alpha_2)$, $(3,2,\alpha_3)$, $(3,3,\alpha_2)$, $(3,3,\alpha_3)$, $(3,4,\alpha_1)$, $(3,4,\alpha_2)$, $(3,4,\alpha_3)$, $(4,3,\alpha_3)$
$r > \|0.05\|$	$(2,5,\alpha_3)$, $(3,2,\alpha_1)$, $(3,2,\alpha_2)$, $(3,3,\alpha_1)$, $(4,2,\alpha_1)$, $(4,2,\alpha_2)$, $(4,2,\alpha_3)$, $(4,3,\alpha_1)$, $(4,3,\alpha_2)$

7.1.3 Simultaneous and Individual Strategies & their Impact on Allocation Efficiency

While for several configurations deviation is only beneficial in a negligible range, others are prone to beneficial mal-reporting of the services' true costs (cp. Table 7.11). The latter need to undergo a closing investigation.

7.1.3.1 Simulation Model and Settings

The problem is modeled as an n-person game with each node representing a service offer. Again, without loss of generality, each service provider owns exactly one single service offer within the SVN. Furthermore, the consideration of the bidding strategies is restricted to price bids only.[17] An independent simulation for each of the tested network configurations is conducted; within this simulation, an initial network topology is randomly generated analogously to the simulations conducted in Section 7.1.2. In each of the simulation rounds, each service

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[16] A Wilcoxon signed-rank test must be applied since the data is not normally distributed (tested by means of a Kolmogorov-Smirnov test) and the number of observations is too small to assume normally distributed data.

[17] Subject to the simplifying assumption that the utility granted by a service provider to the system is monotonically increasing with a higher quality offered and monotonically decreasing when the offered quality is lower, strategies for setting prices and quality attributes can be substituted.

$v_j \in V$ has to choose a strategy, that is, an action r out of its action set $\mathcal{R}_j$. The action set is identical for each service, consisting of discrete manipulation steps $r \in \{-0.5, -0,4, -0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3, 0.4, 0.5\}$ that are applied to each incoming edge of v_j.

Service provider v_j's utility $u^s_{j,r}$ resulting from playing action r in simulation round s is, however, not only dependent on v_j's own action: no service provider can offer a complex service by itself. Therefore, its utility additionally depends on other providers' actions, the network topology, and the service customer's preferences.

In the simulation at hand, the strategies of the agents are determined in a reinforcement learning approach. Reinforcement learning is known as a goal directed, trial and error learning procedure [309]. It is "a way of programming agents by reward and punishment without needing to specify how the task is to be achieved" [184]. That is, it can be used in a model-free situation. Agents learn from rewards, that is, feedback received in the past with respect to certain performed actions. By trial and error, agents explore their action space in order to determine the best strategy subject to an interaction with the environment in order to achieve a particular goal. Reinforcement learning is certainly not supportable for any given problem, yet the methodology has proven to be a prudential approach to tackle model-free, uncertain, and possibly dynamic environments [97].

Each node v_j assigns a fitness value $f^s_{j,r}$ to each possible action $r \in \mathcal{R}_j$ in each simulation round. The fitness of the chosen action is updated at the end of each simulation round according to the following update rule that depends on the feedback $u^s_{j,r}$.

$$f^s_{j,r} = \beta \cdot f^{s-1}_{j,r} + (1 - \beta) \cdot u^s_{j,r} \tag{7.14}$$

The learning rate $\beta \in [0;1]$ controls the impact of the currently chosen action's fitness on the feedback that has been collected for this action in the previous rounds. Actions are chosen according to a probability choice rule $q^s_{j,r}$ based on the action's fitness and the fitness of each other action.

$$q^s_{j,r} = \frac{f^s_{j,r}}{\sum_{\mathcal{R}_j} f^s_{j,r}} \tag{7.15}$$

The first round of the simulation starts with the same probability choice rule $q^s_{j,r}$ for each action. Each service provider chooses an action according to the choice rule and updates its fitness based on the feedback. This procedure is simultaneously repeated 2000 times, considering the first 500 rounds as the training phase while the following 1500 rounds' data is consulted for the evaluation.[18] To be more precise,

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[18] The simulation data shows that as early as after 1000 rounds (including the training phase), the simulation results do not significantly differ from the results after 2000 rounds anymore. Nevertheless, a sensitivity analysis was performed for selected network configurations which also tested 5000 and 10,000 rounds, yielding the same tendencies than the performed simulation with 2000 rounds.

the data is aggregated in two steps. First, the fitness of each provider's actions is aggregated over the last 1500 rounds (cp. Equation 7.16). Thereafter, these node-based average values are aggregated over all n service providers in the SVN (cp. Equation 7.17).

$$\bar{E}_j(f_{j,r}) = \sum_{s=501}^{2000} f_{j,r}^s \tag{7.16}$$

$$\bar{E}(f_r) = \sum_{v_j \in V} \bar{E}_j(f_{j,r}) \tag{7.17}$$

Furthermore, the count of efficient complex service allocations is collected. Whenever the allocated path minimizes the sum of participating services' costs, allocative efficiency can be approved. Moreover, the relative welfare w^s of each round's allocation is computed by dividing the actual welfare $\mathcal{W}^s$ by the maximum welfare $\mathcal{W}^*$. We can therefore state both the percentage of allocative efficient choices and the relative achievement of welfare for each simulation.

Altogether, each simulation is conducted 30 times per configuration. Based on the averaged data from each of these simulations, statements on the significance of some actions being favored over others can be made. Figure 7.9 gives an overview on the simulation model.

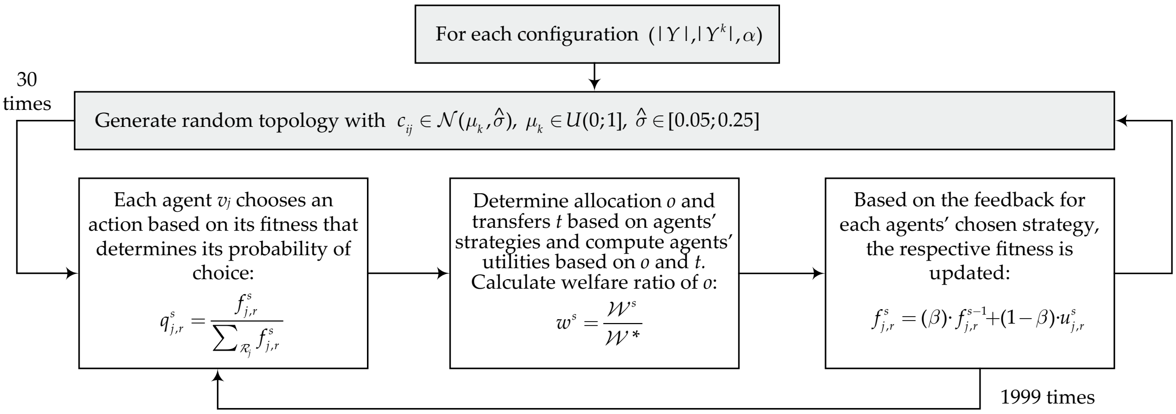

Figure 7.9: Bidding strategies: Simulation model (simultaneous and individual strategies)

Importantly, above-described evaluation is not only conducted for the PRTF, but also for the benchmark ETF-2. Note that the ETF-1 is not tested in this simulation due to its distribution logic that does only include allocated services: services which are close to never allocated receive zero payments which lets them play arbitrary strategies: the action's fitness values level off to zero. However, if, by a certain combination of other provider's actions, such a close-to-never-allocated service v_j is actually chosen, the fitness of v_j's played action in that round spurts upwards and may not be balanced any more. Such events are likely to distort the resulting fitness values.

Table 7.12 summarizes the simulation settings for the evaluation of the bidding strategies focussing on the tested configurations. Note that the variable customer's willingness to pay α_i is not randomly chosen from an interval as done in Section 7.1.2. In order to restrict the influence of changing parameters and to retain comparability of simulation rounds with respect to the feedback given to the agents and the fitness of their actions, $\alpha \in \{1 \cdot |Y|, 2 \cdot |Y|, 4 \cdot |Y|\}$ is set as a constant.

Table 7.12: Bidding strategies: Simulation settings (simultaneous and individual strategies)

Tested configurations $(|Y|, |Y^k|, \alpha)$	$\{(2,5,8), (3,2,3), (3,2,6), (3,3,3), (4,2,4), (4,2,8), (4,2,16), (4,3,4), (4,3,8)\}$
Network density	1.0
Number of simulation rounds	2000 (of which 500 are considered as training phase)
Simulations per network configuration	30

7.1.3.2 Simulation Results

Before interpreting the resulting data of the simulation, it is certainly worth mentioning that the simulation model somewhat trivializes the interplay of strategic actions. Equation (7.17) aggregates the fitness values of the available actions over all participating services, thereby treating them equally regardless of their internal cost structure. Nevertheless, the simulation can be used as an indicator, singling out actions that are more profitable than others *on average*.

Incentive Compatibility

These aggregated results over all services and over all of the 30 conducted simulations per configuration resulting in $\bar{E}(f_r)$ for each manipulation step and for each transfer rule are shown in Tables 7.13 and 7.14. In more detail, the tables output the relative aggregated fitness value AF_r for each manipulation rate, which is calculated as follows:

$$AF_r := \frac{\bar{E}(f_r)}{\sum_{i \in \mathcal{R}} \bar{E}(f_i)} \tag{7.18}$$

AF_r is listed for each tested configuration (cp. Table 7.12) and for the PRTF and the ETF-2. For each of the configurations and transfer rules, the manipulation rate r^{max}, which yields the maximum fitness, is indicated in the bottom line of the tables. In other words, r^{max} is the action that accounts for the highest feedback over the tested 1500 rounds, aggregated over all services. Within a configuration and a transfer rule, the significance of r^{max} against other manipulation rates is tested via a Wilcoxon signed-rank test.[19] The following alternative hypothesis is tested: *The fitness value r^{max} is higher than the fitness values for each of the other manipulation rates $r \in \mathcal{R} \setminus \{r^{max}\}$.* Such significance is indicated by the asterisks in the table row that includes r^{max} for the PRTF.

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[19] A Wilcoxon signed-rank test must be applied since *(i)* the data is not normally distributed which was confirmed by means of a Kolmogorov-Smirnov test and *(ii)* the number of observations is too small to assume normally distributed data.

Table 7.13: Fitness of the services' manipulation strategies applying simultaneous and individual actions (1). * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	(2,5,8)		**(3,2,3)**		**(3,2,6)**		**(3,3,3)**	
r	$\bar{E}(f_r)$							
	PRTF	ETF-2	PRTF	ETF-2	PRTF	ETF-2	PRTF	ETF-2
-0.5	0.0902	0.0866	0.0656	0.0774	0.0866	0.0822	0.0655	0.0821
-0.4	0.0908	0.0876	0.0773	0.0831	0.0886	0.0839	0.0754	0.0868
-0.3	0.0912	0.0880	0.0911	0.0809	0.0902	0.0858	0.0853	0.0885
-0.2	0.0917	0.0886	0.0948	0.0878	0.0916	0.0864	0.0980	0.0915
-0.1	0.0921	0.0891	0.1027	0.0872	0.0925	0.0884	0.1019	0.0930
0	0.0918	0.0907	0.1043	0.0930	0.0928	0.0910	0.1057	0.0968
0.1	0.0914	0.0924	0.1013	0.0987	0.0927	0.0933	0.1072	0.0986
0.2	0.0910	0.0934	0.1004	0.0983	0.0924	0.0949	0.0989	0.0972
0.3	0.0906	0.0930	0.0917	0.1028	0.0917	0.0952	0.0928	0.1003
0.4	0.0901	0.0949	0.0890	0.0973	0.0911	0.0986	0.0870	0.0852
0.5	0.0893	0.0958	0.0818	0.0933	0.0899	0.1004	0.0823	0.0799
r^{max}	-0.1*	0.5**	0**	0.3**	0*	0.5**	0.1**	0.3**

Table 7.14: Fitness of the services' manipulation strategies applying simultaneous and individual actions (2). * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	(4,2,4)		**(4,2,8)**		**(4,2,16)**		**(4,3,4)**		**(4,3,8)**	
r	$\bar{E}(f_r)$									
	PRTF	ETF-2	PRTF	ETF-2	PRTF	ETF-2	PRTF	ETF-2	PRTF	ETF-2
-0.5	0.0644	0.0817	0.0873	0.0832	0.0895	0.0832	0.0844	0.0846	0.0849	0.0833
-0.4	0.0740	0.0862	0.0887	0.0854	0.0895	0.0854	0.0873	0.0862	0.0872	0.0850
-0.3	0.0880	0.0849	0.0899	0.0856	0.0892	0.0858	0.0899	0.0869	0.0895	0.0857
-0.2	0.0931	0.0890	0.0911	0.0867	0.0911	0.0851	0.0918	0.0878	0.0914	0.0873
-0.1	0.0972	0.0892	0.0920	0.0874	0.0909	0.0879	0.0931	0.0889	0.0930	0.0884
0	0.1016	0.0929	0.0925	0.0908	0.0920	0.0908	0.0934	0.0913	0.0932	0.0911
0.1	0.1014	0.0956	0.0924	0.0945	0.0915	0.0939	0.0932	0.0935	0.0931	0.0940
0.2	0.0992	0.0964	0.0923	0.0947	0.0914	0.0955	0.0929	0.0941	0.0929	0.0951
0.3	0.0961	0.0973	0.0916	0.0942	0.0916	0.0937	0.0922	0.0942	0.0924	0.0948
0.4	0.0956	0.0953	0.0915	0.0977	0.0916	0.0976	0.0915	0.0958	0.0917	0.0972
0.5	0.0894	0.0914	0.0907	0.0999	0.0917	0.0995	0.0903	0.0967	0.0907	0.0980
r^{max}	0**	0.3**	0*	0.5**	0**	0.5**	0**	0.5**	0*	0.5**

Evaluating the simultaneous data shown in Tables 7.13 and 7.14, the indications given in Section 7.1.2 take shape: from the unilateral simulation we have learned that the PRTF tends to an undercutting strategy of service providers in configurations with a high Δ. In contrast, applying symmetric strategies, the utility of manipulation and of truth-telling was nearly identical (cp. e.g. Figure 7.7b). These insights materialize in the fitness values for $(2,5,8)$. For the PRTF, all fitness values are rather balanced, however, showing a significant tendency towards $r^{max} = -0.1$ which coincides with the unilateral strategy analysis. AF_r given the ETF-2 peaks at $r^{max} = 0.5$.[20] Compared to the (at least) weakly preferred truth-telling strategy in the symmetric simulation setting (cp. Section 7.1.2.3), the simulation in this section shows that manipulation seems to prevail after all in the ETF-2 case.[21]

For the PRTF, $(4,2,4)$ yielded the highest profitable manipulation rate in the unilateral case, therefore it is interesting to observe how strategies evolve in the simultaneous, individual simulation. In general, fitness values tend to be slightly higher for overbidding compared to undercutting, however, the highest fitness is significantly held by $r = 0$, that is, truth-telling. In ETF-2, service providers' highest averaged fitness values are to be found at $r = 0.3$.

For further detailed results, please refer to Tables 7.13 and 7.14. In summary, the simulation shows that, applying the PRTF, manipulations are only beneficial in a range up to $r = |0.1|$ in average if service providers simultaneously play individual actions. In the ETF-2, overbidding by 30% and more is profitable. These results complete the evaluation of Hypothesis 7.1 for the remaining network configurations tested in this section, which can thus be affirmed for each of the network configuration listed in Table 7.4.

Allocative Efficiency

In the last analysis of this section, allocative efficiency is investigated, looking at two distinct indicators: *relative welfare* $\mathcal{W}^{rel}$ and the *efficient allocation ratio* AR^{eff}. The relative welfare w^s of an allocation in round s is computed by dividing the round's actual welfare $\mathcal{W}^s$ by the maximum possible welfare $\mathcal{W}^*$. These values can be added up to the overall relative welfare $\mathcal{W}^{rel} = \frac{1}{|s|}\sum_s w^s$.

As stated in Section 7.1.1, an allocation is efficient whenever the complex service that maximizes the allocation function assuming truth-telling is chosen – regardless of the included services revealing their true type or not. This fact is important to note with respect to the percentage of efficient allocations AR^{eff} compared to all 1500 observed allocations per configuration. Again, for each configuration, PRTF-based results and results yielded by applying the ETF-2 are compared via a Wilcoxon signed-rank test. The results are summarized in Table 7.15.

Obviously, both indicators are strongly interconnected: whenever an efficient allocation is chosen, both $\mathcal{W}^{rel}$ and AR^{eff} are positively affected. However, the

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[20] The evaluation was conducted with a manipulation rate restricted to the interval $[-0.5; 0.5]$. Therefore, the manipulation rates $r^{max} = 0.5$ that result in some network configuration may even increase if $r > 0.5$ are tested.

[21] In addition, in the symmetric case, several network configuration yielded nearly identical utility ratios for undercutting, truth-telling, and overbidding (cp. e.g. Figure B.4). Therefore, the profitable deviation observed in this section does not contradict the results from Section 7.1.2.3.

Table 7.15: Evaluation of allocative efficiency: Comparing relative welfare and efficient allocation ratio applying the PRTF and the ETF-2. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	$\mathcal{W}^{rel}$		AR^{eff}	
	PRTF	ETF-2	PRTF	ETF-2
(2,5,8)	0.9539**	0.8580	87.75%**	75.92%
(3,2,3)	0.9494**	0.8716	85.13%**	78.45%
(3,2,6)	0.9808**	0.9045	91.10%**	84.33%
(3,3,3)	0.9470**	0.9011	86.38%**	83.85%
(4,2,4)	0.9379**	0.8769	84.77%**	80.41%
(4,2,8)	0.9656**	0.8688	90.54%**	78.20%
(4,2,16)	0.9834**	0.8410	91.83%**	73.25%
(4,3,4)	0.9619**	0.8395	89.86%**	72.46%
(4,3,8)	0.9905**	0.8478	92.35%**	73.92%

expressiveness of the two measures differs. While the relative welfare strongly depends on the parametrization of the simulation, the efficient allocation ratio is more insightful. Ranging from 92.35 % to 84.77% depending on the underlying network configuration, allocative efficient paths are chosen significantly more often in the PRTF case than when applying the ETF-2. Certainly, these investigations were only made for some of the tested network configurations, however, their results in terms of incentive compatibility suggest transferability to the other scenarios rated as approximately incentive compatible after the simulation series conducted in Section 7.1.2.

In summary, isolatedly looking at allocation efficiency does not suffice to make statements on truthfulness whose importance with respect to other network design properties will be discussed in Section 7.1.4. Untruthful bidding of service providers *can* also lead to an efficient outcome, however, only truthfulness guarantees allocative efficiency in any case.

7.1.4 Summary & Implications

In Section 7.1, the co-opetition mechanism's vulnerability to strategic bidding, and in this course, also its degree of allocative efficiency was evaluated. Technically, the power ratio-based transfer function is prone to profitable manipulation. On the other hand, allocation efficiency holds both for truth-telling and for situations in which service providers deviate from their true type, however, the same complex service is allocated than if assuming truthful revelation of services' types. In the current section, several agent-based simulation series were conducted, eventually showing that

- the co-opetition mechanism does, in average, reach a high degree of incentive compatibility for several configurations and customer types, and does only allow for moderate deviation of services' price bids in the range of -10% and 10%, and

- the co-opetition mechanism and its PR-based transfer function beats both more competitive and less competitive alternative transfer functions (ETF-1 and ETF-2) in several cases.

Table 7.16 summarizes the average expected bidding strategies in the co-opetition mechanism that were collected by the different simulations presented in Section 7.1, and thus, the range of expected average equilibrium strategies. In addition, the simulation-based results show that the co-opetition mechanism has the potential to retain a high degree of allocation efficiency in the tested configurations, thereby also performing significantly better than the tested benchmark ETF-2.

As stated in Section 4.1, incentive compatibility is a secondary property that is not directly pursued by the design of the PRTF. However, incentive compatibility indirectly brings about favorable effects for the fairness property of the co-opetition mechanism: as summarized in Section 6.1.5, the symmetry and additivity characteristics only apply for the co-opetition mechanism in a wider sense, that is, in respect of the reported types and the power ratio component of the transfer function t^2. Replacing transfers by the service providers' utilities, fairness properties also apply for the co-opetition mechanism in its entire scope if truth-revelation is an equilibrium strategy. Since the PRTF does not allow for substantial deviation from the service providers' true types with respect to the tested configurations, the fairness property can approximately be widened to the entire co-opetition mechanism.

Table 7.16: Network configurations and their manipulation robustness: Final results. $i \in \{1,2,3\}$

Average expected manipulation	Network configuration
$r \leq \|0.05\|$	$(2,2,\alpha_i)$, $(2,3,\alpha_i)$, $(2,4,\alpha_i)$, $(2,5,\alpha_1)$, $(2,5,\alpha_2)$, $(3,2,\alpha_i)$, $(3,3,\alpha_2)$, $(3,3,\alpha_3)$, $(3,4,\alpha_i)$, $(4,2,\alpha_i)$, $(4,3,\alpha_i)$
$\|0.05\| \leq r \leq \|0.1\|$	$(2,5,\alpha_3)$, $(3,3,\alpha_1)$

7.2 Individual Rationality

Individual rationality imposes the requirement to distribute, at least, their reservation utilites to all mechanism participants. Utility can be measured in different "intensities": concentrating on the service provider-side, participation in the SVN must be indicated and confirmed before the service providers actually know the outcome. It is also dependent on the other participants' types and strategies which are unknown – a service provider can merely exhibit a prior about the distribution of other agents' types. Therefore, ex interim individual rationality as introduced in Section 3.1.3 is appropriate in the setting at hand. Fixing the reservation utility to zero, ex interim individual rationality denotes a situation in which service providers, in average, do not lose by participating in the mechanism.

$$\forall\, v_j \in V : \bar{E}(u_j(F^*)) \geq 0 \tag{7.19}$$

As Parkes [257] points out, individual rationality is an important design goal to make a mechanism sustainable: participants have to take part on a voluntary basis, which is only given if Equation (7.19) holds. In general, a negative utility u_j with respect to a service v_j offered is possible if and only if both of the following two cases occur:

1. Recall that non-allocated services always receive a payment $t_j \geq 0$ since $c_{ij} = 0$. Thus, $E(u_j(F^*)) \geq 0 \,\forall\, v_j \notin W^*$. Therefore, attention of the analysis of ex interim individual rationality can be restricted to allocated services. That is, service v_j must be allocated via one of its links e_{ij} (with $v_j \in Y^k$, $v_i \in Y^{k-1}$, $e_{ij} \in E(W^*)$), and

2. the service provider's strategy with respect to v_j is to undercut the true costs c_{ij}. Only in this case, $u_j < 0$ is possible at all. Recall that the utility of a service is defined as $u_j = t_j - c_{ij} = t_j^1 - c_{ij} + t_j^2$ if v_j is allocated via e_{ij}. Overstating c_{ij} lowers the allocation probability, however, ensures a positive utility: the utility from t^1 must be positive since $p_{ij} - c_{ij} > 0$. Further, $t^2 \geq 0$ always holds (cp. Equations 5.15 and 5.18). Analogically, if the service's true type is revealed ($p_{ij} = c_{ij}$), the utility from t^1 is zero and, as stated above, the PR is always non-negative. Only in case of undercutting, i.e. $p_{ij} \leq c_{ij}$, u_j can turn negative if the losses incurred via t^1 are not compensated by v_j's power ratio.[22]

Section 7.1 thoroughly demonstrated that equilibrium strategies in respect of the agents bidding cannot be stated precisely, however, a strong indication of expected average bidding strategies was given in Table 7.16. As ex interim individual rationality is based on the expected utilities, it is also appropriate to utilize the average expected allocation probabilities. This is done by the multiple rounds included in the simulations conducted in Section 7.1. In order to make statements on services' utilities, the aggregated utility ratios $R_j^{r_{uni}}$ and $R_j^{r_{sym}}$ are consulted: as long as $R_j^r \geq 0$ in average, service providers do not expect to incur losses by participating. Table 7.17 shows the manipulation rates r^{neg} from Section 7.1.2 that turn R_j^r into a negative value for both the unilateral and the symmetric case.

In configurations with a low α, unilateral and symmetric undercutting can quickly lead to situations which lets service providers leave the transaction with a negative utility. Losses from t^1 cannot be compensated by t^2. This is different if a larger surplus is distributed: in the unilateral case, losses are still possible since single providers are more likely to be allocated the lower their price bid is – again, these losses cannot be compensated after a certain manipulation level is reached. In the symmetric case, undercutting does not change the allocation, that is, the most efficient services are still guaranteed to be picked by the allocation function. In settings with a high α, allocated services are still likely to compensate losses from t^1 by

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[22] For a more detailed summary of the coherency between allocation and changes in the transfer function in case of bid price manipulation, please refer to Section 7.1.1, in particular Figure 7.1.

Table 7.17: Manipulation strategies accounting for an expected negative utility. – denotes that there is no manipulation rate to turn R_j^r into an expected negative value.

Configuration	r_{uni}^{neg}	r_{sym}^{neg}
$(2,2,\alpha_1)$	-0.45	-0.45
$(2,2,\alpha_2)$	-0.7	–
$(2,2,\alpha_3)$	–	–
$(2,3,\alpha_1)$	-0.4	-0.65
$(2,3,\alpha_2)$	-0.7	–
$(2,3,\alpha_3)$	–	–
$(2,4,\alpha_1)$	-0.4	–
$(2,4,\alpha_2)$	-0.6	–
$(2,4,\alpha_3)$	–	–
$(2,5,\alpha_1)$	-0.4	–
$(2,5,\alpha_2)$	-0.55	–
$(2,5,\alpha_3)$	–	–
$(3,2,\alpha_1)$	-0.3	-0.3
$(3,2,\alpha_2)$	-0.4	–
$(3,2,\alpha_3)$	–	–
$(3,3,\alpha_1)$	-0.3	-0.4
$(3,3,\alpha_2)$	-0.4	–
$(3,3,\alpha_3)$	-0.85	–
$(3,4,\alpha_1)$	-0.35	-0.3
$(3,4,\alpha_2)$	-0.4	-0.4
$(3,4,\alpha_3)$	-0.75	-0.75
$(4,2,\alpha_1)$	-0.25	-0.25
$(4,2,\alpha_2)$	-0.3	-0.4
$(4,2,\alpha_3)$	-0.65	–
$(4,3,\alpha_1)$	-0.4	-0.4
$(4,3,\alpha_2)$	-0.35	–
$(4,3,\alpha_3)$	-0.55	–

the PR. A smaller α can actually lead to negative utilities if the share in the PR is too low to compensate every service provider's loss from undercutting.[23]

These results are compared to the average equilibrium bidding strategies of service providers shown in Table 7.16. In none of the tested configurations, average equilibrium bidding strategies are situated in a range of $-0.95 \leq r \leq -0.25$. What is more, for the settings $(|Y|,|Y^k|,\alpha_1)$ that are more prone to negative utility, results of Sections 7.1.2 and 7.1.3 suggest that undercutting is never a profitable strategy. In some of the remaining settings slight tendencies to undercutting can occur in equilibrium, however, they are far from approaching manipulation rates that actually yield a negative utility ratio.

Therefore, based on the simulation results from Section 7.1, ex interim individual rationality, that is, a utility that is in average non-negative in equilibrium, can be stated for the co-opetition mechanism. That is, based on expected utilities of service providers, Requirement 4.8 can be acknowledged.

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[23] Please refer to 7.1.2.4 for a more detailed analysis of how strategies evolve in the symmetric simulation case.

7.3 Summary

Classic mechanism design objectives partly step back in favor of desired network-related properties by the co-opetition mechanism. More precisely, as outlined in Section 4.1, incentive compatibility, and therefore also allocative efficiency cannot be directly targeted by the mechanism implementation as established in Chapter 5. Nevertheless, on an implicit level, it becomes preferable that the co-opetition mechanism exhibits a certain robustness against strategic behavior of participants for several reasons. First, truthful revelation of service providers' types is the only strategy profile that definitely assures a welfare-maximizing outcome. As shown in Section 7.1.1, an efficient allocation is also possible if service providers reveal their true type – however, cannot be ensured as long as strategic manipulation is profitable. In this connection, allocative efficiency, which is also not a part of the co-opetition mechanism's social choice, turns out to be desirable to some degree as the most efficient service providers should be regularly allocated in order to benefit from their high performance. Second, as discussed in Section 6.1.5, fairness-related requirements only apply for the power ratio. Subject to some slight changes to the properties' definitions, the fairness characteristics can approximately be transferred to the co-opetition mechanism as a whole if incentive compatibility is fulfilled to a high degree. Picking up the results from Section 6.1, fairness is a crucial property of the co-opetition mechanism to induce the service providers' very willingness to participate in the SVN.

The core contribution of this chapter was to analyze the co-opetition mechanism's vulnerability to strategic manipulation of service providers' bids. This question was tackled by means of a series of agent-based simulations. Taking a multitude of different scenarios including various configurations of approaching customers' service inquiries, service offers, and competitive situations as a basis, most of them exhibited strong tendencies towards service providers playing average equilibrium strategies in close proximity to their true types. More precisely, profitable deviation rates of 5% or less from true costs could be shown in more than 90% of all tested network configurations.

Moreover, defined as requirement to enable a sustainable business in SVNs, budget balance and and individual rationality are retained by the co-opetition mechanism. While budget balance is fulfilled by design as shown in Sections 5.4 and 6.1.1, ex interim individual rationality could be shown based on the above-named numerical results. Since service providers do not expect to lose money by participating in the co-opetition mechanism, per se, there is nothing to prevent their participation assuming an outside option that yields a zero utility.

Summarizing the evaluation part of this thesis, it remains to be stated that Chapters 6 and 7 addressed Research Question 5. By providing theoretical and numerical approaches, it was *(i)* not only shown how the co-opetition mechanism can be evaluated regarding its properties but also *(ii)* substantiated that the co-opetition mechanism actually implements the social choice as installed in Section 4.1.2. Moreover, although not particularly designed to fulfill incentive compatibility and allocative efficiency, the co-opetition mechanism satisfies both of these classic mechanism design desiderata to a high degree.

Part IV

Finale

Chapter 8

Conclusion & Outlook

This thesis was motivated by the tremendous changes observed in the software industry. While economic and technical issues arising from traditional software vendors turning into service providers have already been picked up in academia, another wave of innovation suggesting the creation of value-added complex (Web) services as a joint, cross-organizational process has only been partly addressed by academic literature so far. Whereas scholars already dedicate intensified research activity to technology-driven approaches enabling the composition of Web services to complex and valuable business applications, economic considerations are lagging behind. The latter aspect is where the work at hand is focussing on. It yields a comprehensive mechanism design approach to coordinate service providers that engage in cross-company value creation processes subject to both cooperative and competitive relationships.

Section 8.1 will summarize the major contributions of this thesis by revisiting the research questions outlined in Section 1.1. Section 8.2 will discuss limitations of the approach followed by an elaboration of future research directions. Section 8.3 will point out related research lines to complement the contributions made by this thesis.

8.1 Contribution

The work at hand is on designing a mechanism that is tailored to a special kind of networked economy which includes both competition and cooperation as inherent building blocks: service value networks (SVNs). More precisely, the network operator's viewpoint is held, seeking for a scheme that sets suitable incentives to make SVNs attractive for participants in their launch phase and, at the same time, induces a certain behavior of agents that is in line with the overall system objectives pursued. Hence, the main contribution and major focus of this work is to implement a mechanism that coordinates service allocation and value distribution subject to crucial design goals that are determined by the co-opetitve environment. This challenge is addressed by Research Question 4:

Research Question 4 $\prec$IMPLEMENTATION OF THE CO-OPETITION MECHANISM$\succ$.
How can the co-opetition mechanism be implemented to meet both requirements from net-

work design and from classic mechanism design subject to its ability to handle multiattribute and sequence-sensitive complex services?

However, in order to provide an answer to this research question, several related questions have to be addressed. On the one hand, they lead to the topic by dealing with important prerequisites. On the other hand, they are required to top off Research Question 4. Thus, several additional contributions to coalesce around the implementation of the co-opetition mechanism are made in this thesis.

As a preparation for a theoretically sound mechanism design approach that can be transferred to the application scenario at hand, both economic foundations and the application environment have to be scrutinized and understood in detail. At first, the characteristics of the surrounding environment of the co-opetition mechanism were analyzed. As indicated in the introduction to this chapter, classic vendors turn into service providers, offering software "as-a-service" instead of selling and installing software products at customer site. In order to understand the consequences of this development, services and their importance for the economy were discussed in Section 2.1. In more detail, services, electronic services, and Web services were defined in a constructive approach in order to establish a common basic understanding for the trading objects of the co-opetition mechanism: Web services. According to the definition that was provided, this type of service also includes the wide field of software-as-a-service (SaaS) offerings.

Web services in general exhibit beneficial features that can be exploited for advanced, cross-organizational value creation. First, Web services are oftentimes requested with specific functional and non-functional requirements in mind. Second, their modularity and Web-based communication protocol give rise to an automated composition into complex, value-added services, which supports today's trend towards companies' concentration on their core competencies. Complex services are assembled from modules offered by diverse service providers, thereby creating customized solutions that meet virtually any kind of customer demand. In Section 2.2, it was argued that these characteristics entail the long valley of services, thereby extending the well-known long tail phenomenon by a third dimension "composition depth". At the same time, this focus on services overcomes ever-pled objections that query the long tail's general "value proposition". The explicit elaboration of the long valley effect is novel to academic literature, concluding that combinatorics of constructible Web services are optimally exploited by a newly arising form of networked organizations introduced as service value networks. In a comprehensive effort to differentiate SVNs from related concepts, *(i)* automated on-demand service composition, that is, an automatically performed search for an optimal[1] complex service, and *(ii)* the network orchestration platform's universal accessability were identified as distinctive characteristics of SVNs. In this course, Research Question 1 was addressed:

Research Question 1 ≺CHARACTERISTICS AND EMERGENCE OF SERVICE VALUE NETWORKS≻. *How can service value networks be defined and which economic factors drive their emergence?*

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[1] Herein, optimality can be defined in different ways according to the specified goal, which can, for instance, be welfare maximization.

A graph-based formalization of SVNs was presented that does not only capture the presence of substitutive and complementary service components at the same time, but also the importance of the sequence of service components in a complex service. Each combination of services can potentially create a new customer-demanded functionality, thereby stressing the long valley effect in SVNs. Current closely related examples, for instance, TEXO as an ambitious research endeavor to holistically grasp challenges of such networked service markets, rounded off Chapter 2.2.

After thoroughly discussing the basics of the trading objects of the co-opetition mechanism, closely related economic foundations were introduced in Section 3. The SVN environment exhibits both components of competitive environments that breed selfish behavior of participants and the requirement to cooperatively offer a complex service as a joint value creation activity. Therefore, essential elements from non-cooperative as well as cooperative game theory were scrutinized. On the one hand, mechanism design was chosen and introduced as the general methodology to be applied (cp. Section 3.1): mechanism design is not about what will happen in a specific interaction of various agents, but rather tackles the issue of having a desired outcome in mind and to comprehend which strategic interaction and which setting could lead to a course of action that implements this outcome. The latter shall be realized even if participants act opportunistically in order to maximize their individual utility. Yet, mechanism design in its classic form is not ideally suited: agents in SVNs are selfish, however, they can only reach certain goals as a team. The provisioning of a complex service requires a joint effort. Therefore, the foundations of value distribution in network-based, cooperative situations were introduced in Section 3.2. The consolidation of these two fundamentals, mechanism design and cooperative as well as network games lead to the proposal of a novel form of network-based incentive engineering approach called *networked mechanism design* (cp. Research Question 2).

Research Question 2 ≺NETWORKED MECHANISM DESIGN≻. *How can classic mechanism design be mapped to networked mechanism design?*

The merit of networked mechanism design is to accentuate alternative properties that may prevail over traditional economic desiderata when designing a business in a networked environment. Therefore, classic desiderata are queued up within novel network-related targets to some extent. Design objectives of the co-opetition mechanism were raised in a thorough environmental analysis as presented in Section 4.1, thereby addressing Research Question 3.

Research Question 3 ≺MECHANISM REQUIREMENTS IN SERVICE VALUE NETWORKS≻. *Which are the design objectives of the co-opetition mechanism in order to suit the requirements of early service value networks?*

According to the environmental analysis, network growth, readiness to deliver, fair, monotonic and unique payoffs, and interconnectedness were identified as desirable properties of the co-opetition mechanism. Budget balance and individual rationality as traditional economic properties shall be retained while incentive compatibility and allocative efficiency step behind, however, must still be kept in focus. Additionally, the ability to handle multiple quality of service attributes and the support of a service composition's sequence are mandatory requirements to apply the mechanism in SVNs.

These design objectives in turn laid the groundwork for the co-opetition mechanism as presented in Section 5. Based on a brief introduction of the mechanism's underlying auction type, namely multiattribute reverse auctions, a bidding language that suits the multiattribute character of Web services was presented. With a suitable auction type and bidding language available, this thesis' central Research Question 4 could be tackled. To this end, the power ratio (PR) was elaborated as the heart of the co-opetition mechanism. Following a whole new direction of distributing revenues in commercial services networks, the PR's essence is not only to reward allocated service providers, but also service providers on standby. That is, the circumstance that service providers in the SVN must not necessarily be the "best ones" in order to create value for the system was included in the transfer payment logic. To this end, a value function to express the value generated by the complex service offered within the SVN was designed based on the multiattribute customer request. The PR measures this monetized value contributed to the SVN by a single provider in terms of its marginal contribution. The computation scheme is based on the Shapley value and is applied to complex services as smallest value-creating unit. By developing such a cooperative solution concept in a non-cooperative mechanism design approach, the co-opetitive character of service value networks was mirrored.

The co-opetition mechanism as the focal deliverable of this thesis was designed to fit the desired properties stated in Research Question 3. In a final step to round off this work, these requirements were evaluated in both analytical and simulative approaches outlined in Chapters 6 and 7:

Research Question 5 ≺EVALUATION OF THE CO-OPETITION MECHANISM≻. *How can the co-opetition mechanism be (numerically and analytically) evaluated regarding its properties?*

In a theoretical analysis, fairness and cooperational monotonicity of the power ratio were proven. Those properties are of prime importance with respect to the fashion of value distribution: if revenues are granted to service providers that are not allocated, fairness must be retained. By also fulfilling cooperational monotonicity, the PR assures that individual contribution is incorporated in a way that an increase in a service provider's (individual) efficiency must at least lead to an identical or a larger payoff. Thereby, competitive forces in SVNs are amplified. Also based on theoretical results, it was shown that the co-opetition mechanism induces a fully intermeshed SVN as a stable result. In other words, each service provider maximizes its utility by being fully linked. That is, being compatible with as many complementary services as possible is a pure strategy Nash equilibrium. Full interconnectedness as a stable state is a strong result, which underscores the co-opetition mechanism's capacity to enhance complementarity. Since the co-opetition mechanism induces incentives for service providers to continuously keep ready their services (i.e., their readiness to deliver) and also yields a unique solution "by design", the last network-related property to be proven was network growth. Elaborated by means of a simulation-based approach, it was shown that the co-opetition mechanism applying the power ratio-based transfer function (PRTF) implements stronger incentives to join an SVN than an otherwise identical mechanism relying on an equal transfer function (ETF-1) which distributes available surplus equally among allocated service providers.

In terms of classic mechanism design goals, incentive compatibility and allocative efficiency were not deliberately included into the design goals for the co-opetition mechanism, however, they must be kept track of due to their relation to other desired properties such as fairness. By dint of a comprehensive agent-based simulation approach, bidding strategies of service providers, and therefore, the co-opetition mechanism's vulnerability to profitable manipulation, were identified subject to different scenarios. It could be shown that *(i)* strategic behavior is clearly limited in realistic network and customer configurations and *(ii)* the co-opetition mechanism applying the PRTF beats a transfer function (ETF-2) that equally distributes available surplus among all participating service providers, thereby hardly setting competitive incentives. Concretizing the former finding, it could be numerically indicated that the co-opetition mechanism can be classified as approximately incentive compatible in more than 90% of the tested configurations, allowing profitable deviation of 5% or less, which also retains allocative efficiency to a high degree.[2] The described simulation series could also be exploited to show that the mechanism is ex interim individual rationality: service providers that take part in an SVN which applies the co-opetition mechanism do not expect to suffer any loss by being included in transactions, and thus are all set to voluntarily participate.

8.2 Limitations of the Approach& Future Work

This section discusses limitations of the approach in a critical appraisal and sketches possible suggested solutions (cp. Section 8.2.1). Directly linked to these issues, Section 8.2.2 raises open research questions that could no be addressed in the work.

8.2.1 Limitations of the Approach

In this Section, limitations to the approach presented in this thesis are summarized. Transitions of open issues and limitation are inherently smooth, therefore, this section is closely related to Section 8.2.2.

Straightforward customer and one-sided incentives

In this thesis, incentive engineering is focussed on the service provider side, translating into two basic assumptions. On the one hand, as stated in Assumption 5.2, strategic behavior of the customer is faded out. It is assumed that a straightforward service customer will truthfully announce its type to the mechanism. On the other hand, the customer's utility is always fully "exhausted". It is assumed that the

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[2] Yet, note that the co-opetition mechanism is not incentive compatible in an analytic sense (cp. Section 7.1.1).

service customer is willing to pay a "premium" in return for being equipped with a perfectly matching complex service.[3] Both restrictions are commonly accepted in literature [195, 259, 45]. Nevertheless, research efforts should continue with a relaxation of the customer-related assumptions: how to extend the mechanism to explicitly include incentives targeted at the customer-side?

An extended mechanism design could explore how and to which extent the sum of power ratios $\Delta = \sum_{v_j \in V} \phi_j$ of service providers (SPs) can be reduced and redistributed to the service customer (SC). A first approach may be a linear *customer-provider ratio* as exemplified in Equation (8.1):[4]

$$\Delta = \underbrace{\beta \cdot \Delta}_{\text{SPs share}} + \underbrace{(1-\beta) \cdot \Delta}_{\text{SC share}} \tag{8.1}$$

That way, budget balance is definitely retained. $\beta \in [0;1]$ defines the factor to determine the monetary share granted to either involved market side. Currently, the co-opetition mechanism sets $\beta = 1$. If we set $\beta < 1$, the properties postulated in the social choice need to be reassessed. Certainly, relaxing assumptions on customer-side brings about additional properties which potentially have to be traded off against the hitherto pursued objectives. In addition, strategic behavior of customers is to be analyzed.

Alternatively, Assumption 5.2 can be relaxed by dropping budget balance. If the surplus Δ is borne by the platform, the allocation function maximizes both customer and provider utility (cp. Section A.2). In this case, the price charged from the customer reduces to the $\mathcal{P}_{F^*}$ for the allocated service F^*. The co-opetition mechanism's properties besides budget balance are retained, manipulation robustness in terms of the customer should additionally be surveyed. The downside of this approach is that overpayments are not controllable and can be arbitrarily high, depending on the difference between a customer's willingness to pay and $\mathcal{P}_{F^*}$.

Therefore, a variation could be the *relative power ratio* which calculates the service providers' relative share in the system's overall utility. It evolves as a direct extension of Equation (5.18) by normalizing the power ratio of each service $v_j \in V$ to the maximum system utility:

$$\phi_j^{rel}(\mathcal{G},\chi) = \frac{\phi_j(\cdot)}{\sum_{v_i \in V} \phi_i(\cdot)} = \frac{\phi_j(\cdot)}{\chi(\mathcal{G})} \tag{8.2}$$

Replacing the PR by its relative version, the platform operator can control the amount of monetary means $\tilde{\Delta}$ to be subsidized. Consequently, according to Equation (8.2), each service v_j is granted a PR-transfer of $\phi_j^{rel}(\cdot) \cdot \tilde{\Delta}$. Again, hitherto postulated components of the co-opetition mechanism's social choice as well as strategic acting on customer-side need to be reviewed. Besides losing budget balance,

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[3] Technically, re-setting the surplus Δ to be distributed via the PR to $(\Delta - \varepsilon)$, with $\varepsilon > 0$ and $\varepsilon \rightarrow 0$, the service customer strictly prefers participating in the co-opetition mechanism over non-participation.

[4] For the foundations and notational details, please refer to Sections 5.2.2 and 5.2.3.

deficiencies have to be accepted in terms of the SVN's interoperability: as shown in Conte et al. [81], adding all available links is not a dominant strategy for service providers anymore. For instance, a service provider can remove a connection at the same time increasing its utility – it just requires that the link removal hurts others more than the considered service provider itself. Such dependencies are possible due to the relative character of the payoff. The same holds true for coalitional monotonicity (cp. Requirements 4.5). By normalizing to $\chi(\mathcal{G})$, the relative power ratio does not solely base its payoff on a service's own contribution, but explicitly involves other services' contributions to the network. As shown by Young [341], such payoff rules may penalize individual initiative to improve efficiency.

These alternative concepts that explicitly include customer-side incentives into the transfer rule show that a careful review is required to identify their strengths and shortcomings and to set them into relation with existing and newly emerging design properties. Related to such an extension, the customer-side should also be an active agent in the simulations that evaluate network growth (cp. Section 6.4).

Simulation-based evaluation of the co-opetition mechanism's properties

Although simulations often yield valuable results and implications, general limitations of the approach must be conceded. Simulation models usually simplify reality to a certain degree. In this thesis, two simulation-based approaches were consulted. The first one was utilized in order to show the co-opetition mechanism's ability to foster network growth (cp. Section 6.4). It incorporates three major simplifications as stated in the following: first, truthful revelation of service providers' types was assumed. While this assumption is acceptable for the co-opetition mechanism, the applied benchmark (ETF-1) cannot be rated approximately truthful in each of the tested network configurations. Second, taking in the latter, statements on performance are partially based on benchmarks. The PRTF does beat the ETF-1, however, it cannot be excluded that other, non-evaluated benchmarks outperform the PRTF. Finally, network effects enjoyed by customers were assumed to be present without explicitly simulating network growth on customer-side. More precisely, an increasing number of service providers opting for the PRTF-based market was assumed to create a larger customer base, again leading to a more valuable network for service providers [15, 188]. Thus, in total, the suggested simulation model includes some particular simplifications that may not allow to fully generalize the results. Still, the data delivers valuable insights into how SVNs evolve subject to the co-opetition mechanism as applied coordination scheme.

A second simulation-based model and setting was used to evaluate classic mechanism design properties in Chapter 7.1. Complexity and runtime were decreased by limiting the agents' strategy spaces to discrete actions, thereby sacrificing accuracy to a certain extent. Yet, by choosing quite small increments between possible actions, statements on the degree of strategic manipulations were kept within reasonable limits. Further, the simulation model presented in Section 7.1.3 considered individual strategies that evolve over time by applying reinforcement learning. This learning model has proven to suit certain model-free situations, however, its appropriateness in the multi-agent environment cannot be undoubtedly affirmed. Although van Dinther [97] showed that reinforcement learning performs well in a multi-agent bidding scenario, it cannot fully represent human behavior. Despite such an inherent degree of distortion, the numerical approaches yielded useful and coherent results whenever the multitude of parameters made theoretical analyses too complex to handle.

In general, in order to back up the results of and implications from the agent-based simulations, further research should take up the examined problem sets and put the numerical results to a test: smaller SVNs can reasonably be reproduced in laboratory experiments, which is likely to shed light on the validity of the simulation-based results.[5]

8.2.2 Future Work

Beyond the accomplishments in this thesis, there are several promising directions in which this research can progress further. Such specific extensions are outlined in the following, exemplified by sample research questions that are eligible to be addressed in future.

Thoughts on fairness: the weighted power ratio

The power ratio itself treats any kind of service equally within a complex service. Put differently, each candidate pool takes a neutral, homogenous role from the SVN operator's view in terms of its positioning (in a sense of "importance") in the network. That is, the power ratio is distributed to services without making a difference between the candidate pools per se. This is certainly a desirable property if functionalities are of similar complexity, for instance, indicated by approximately identical costs.

Yet, such a symmetric distribution might be distorted if functionalities are to be classified "on different levels", that is, quite basic Web services are assembled together with more sophisticated on-demand applications that feature costs amounting to a multiple of the basic services' costs. Still, the power ratio treats them equally in terms of their marginal contribution. Assume a degenerated SVN with two candidate pools which includes one service each. Applying the PR, the services would always share the available surplus in equal parts, no matter if, for instance, one of the services is a CRM application and the other one is a simple storage service.

From a theoretic side, this is straightforward since both services are required for value creation. However, from the participating service providers' side, this might become an issue: a more sophisticated and therefore probably more expensive service is likely to implicitly account for a large share of the customer's willingness to pay. This issue results in power ratios that may be perceived unfair by the provider of the sophisticated service due to the comparatively higher effort put into the co-operations – even though the PR is fair in a game theoretic sense (cp. Section 6.1). Thus, such constellations may legitimate a variation of the power ratio and, thereby,

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[5] Yet, differing results would not necessarily imply that the simulation-based results did not reproduce the theoretical solution properly. The assumption of rational agents cannot always be retained in reality, so that analytically sound outcomes may not be the result of humans' real world behavior.

its fairness perception. It suggests itself to introduce weightings to capture this issue. But how can such a variation be incorporated into the power ratio?

Cooperative game theory yields means to incorporate weightings. Shapley [291] introduced a variant of his value that drops the symmetry axiom. In more detail, it is a generalization of the symmetric variant that attempts to divide generated value by assigning to each agent a weighted average of the marginal contribution it makes to all possible coalitions [74].

Transferred to SVNs, these weightings replace the notion of symmetrically dividing value within complex services. Let $\bar{\lambda} = (\bar{\lambda}_1, \dots, \bar{\lambda}_n)$, $\sum_{v_i \in V} \bar{\lambda}_i = 1$ denote weights for each of the $|V| = n$ services available in an SVN $\mathcal{G}$. Following Shapley [291], Kalai and Samet [185], Monderer et al. [229], Dragan [101], the weighted power ratio ϕ_j^{WPR} for a service $v_j \in V$ can be computed as follows:[6]

$$\phi_j^{WPR}(\mathcal{G}, \chi, \bar{\lambda}) = \bar{\lambda}_j \cdot \sum_{S_m \in S | v_j \in V_m} \bar{\gamma}_{S_m}(\chi(S_m) - \chi(S_m^{-j})) \tag{8.3}$$

with

$$\bar{\gamma}_{S_m} = \sum_{S_h \in S | V_h \cap V_m = \emptyset} \frac{(-1)^{|V_h|}}{\sum\limits_{v_i \in \{V_h \cup V_m\}} \bar{\lambda}_i} \tag{8.4}$$

$\bar{\lambda} = \frac{1}{n}$ for each of the n services yields the power ratio as a special case [185]. Out of Equations (8.3) and (8.4), new questions arise: the weight is determined by the sizes of cooperations and an exogenous parameter $\bar{\lambda}$. How can we determine such weightings for services? In case of different cost classes of services, appropriate weightings per candidate pool must be found that follow some logic that is accepted by the participating service providers. In addition, an adaption of Equations (8.3) and (8.4) away from individual weightings to candidate pools must be carried out. A different logic for setting the weights according to reputations of services rather than to candidate pools is touched on in Section 8.3. Several scholars, for instance, Kalai and Samet [185], Hart and Mas-Colell [150], Levy and McLean [207], Nowak and Radzik [247], present alternative axiomatizations for the weighted Shapley value that include different updated notions on fairness; these properties should be reassessed for the weighted PR due to the modifications made. Moreover, other properties of the co-opetition mechanism's social choice must be reviewed in terms of their transferability to the weighted power ratio.

Bundled and multi-functional service offers

In the present version of the co-opetition mechanism, the underlying SVN model as introduced in Section 2.2.3 is limited to a k-partite graph. However, the co-opetition mechanism's allocation and transfer functions can easily be transferred to an SVN model with relaxed assumptions on its structure, first and foremost, replacing services' strict categorization into candidate pools by a possibility of services covering

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[6] Please refer to Sections 2.2.3 and 5.2 for notational issues.

multiple functionalities in an integrated manner. This becomes a very interesting issue from a strategic point of view, allowing service providers to bundle their services.

Such strategic options give rise to further research questions, such as for example: in which circumstances is it beneficial for service providers to merge services to a bundled offer? On the one hand, assuming no additional costs for interconnectedness, it was shown in Section 6.3 that a fully intermeshed network maximizes the agents' utilities. It remains to be evaluated, in which cases, for two previously unbundled services, a bundling effort that withdraws links from the SVN will lower or increase involved services' expected utilities and how such bundling influences the other services' utilities and strategies. Even if the power ratio of the bundled service is lower than the sum of the two services' payoff if individually offered, bundling might be advantageous for service providers if it cuts costs through collaboratively relying on the same assets, for instance storage or computing resources. On the other hand, in line with the potential of the long valley's third dimension, namely composition depth, merging offerings decreases granularity of services. Thereby, service providers deprive themselves of the opportunity to participate in as many diverse combinations of offerings as possible. In other words, bundling removes possibilities for combinatorics and reduces variability, that is, both possible service instances and re-combinations decrease, and therefore, counteract the general ideology of SVNs. In the medium term, this may also impinge upon service providers' profits. Thus, service provider's strategies in terms of bundling or unbundling should be analyzed as a part of future research.

A related line of research is the consideration of collusion. How does the co-opetition mechanism perform if we switch from a one-shot-game consideration to an iterated game? The latter implies that service providers have the possibility to tacitly collude via their bidding strategy. Indications on how to approach such situations can be found in van Dinther et al. [98].

The co-opetition mechanism in large networks

The co-opetition mechanism is designed for SVNs in their launch phase. Some of the properties of the mechanism's social choice function are directly related to this aim, first and foremost, network growth (Requirement 4.1) and readiness to deliver (Requirement 4.2). Moreover, fairness as stated in Requirement 4.3 and cooperational monotonicity (Requirement 4.5) are also owed to the logic of the power ratio, i.e. distributing payments not only to allocated services, but also to services that are generally able to create value for the SVN. This circumstance gives rise to further research questions: in larger networks, these properties are not necessarily required anymore and may be replaced. Which is the updated social choice in SVNs that have reached a certain size? Which mechanism is suited best to fit this social choice? And what is an optimal network size threshold to switch from the co-opetition mechanism applying the PRTF to a different mechanism that, for instance, restricts the surplus to allocated services?

Updated design goals may be focussed on the classic desiderata incentive compatibility and allocative efficiency, which are only met to a high degree by the co-opetition mechanism in the tested network configurations. In terms of an optimal threshold to switch the mechanism to alternatives that fulfill the above-listed properties, indications can be extracted from the simulations conducted in this thesis. For the matter of incentive compatibility, the results from Section 7.1 suggest the possibility that service providers tend to misreport their types in larger networks if their power ratios decrease and approach those of the other services in absolute terms.[7] In this case, the PR-based payoffs are likely to not have an economically significant impact anymore, revenues can only be made out of an overbidding strategy (in terms of the bid price)[8]. Moreover, in larger networks, tractability requirements from computational mechanism design that can tackle rising complexity caused by an increased number of cooperations and paths within the SVN will definitely become an issue (cp. Section 5.3.1.2, also refer to the next paragraph). Furthermore, after being neutral in terms of revenue distribution in the launch phase of the SVN, revenue maximization objectives of the platform operator may partly replace network design goals. In this connection, fees collected from participants for their membership in the SVN or per transaction come into question [274, 275]. Network growth seems to be constantly observable, even more distinct in larger networks (cp. Section B.1), however, measured in terms of expected utilities. Realized payments are likely to equalize and become infinitesimally small in large networks when applying the PRTF. It is to be evaluated if such small payments set sufficient and viable incentives to actually sustain network growth requirements.

Revisiting computational complexity

Putting computational constraints aside, mechanism design assumes that the correct outcome can be determined as a result of the relevant decentralized information provided within the system [257]. In other words, the typical underlying problem of coordinating decentralized agents that hold private information converts into a centralized scenario. This is also the case in the work at hand: Assumption 5.1 states that the co-opetition mechanism connects all participating agents as a central entity. As shown in Section 5.3, the computation of the power ratio makes the co-opetition mechanism intractable. However, in smaller network scenarios that are realistic in the launch phase of an SVN, the complexity and runtime of sample calculations can be handled within reasonable limits. Still, the computational complexity of the co-opetition mechanism brings about increased computational effort in medium sized network configurations.

Therefore, further research efforts should be put into the approximation of the power ratio. Literature on approximating Shapley-style calculus is quite scarce: Mann and Shapley [214], Owen [254], Bachrach et al. [18], Fatima et al. [117] provide related approaches, however, concentrate on simple voting games, i.e. the Shapley-Shubik index. With respect to the PR, it is not only crucial to test the approximation error of such approaches, but also their compliance with the co-opetition mechanism's social choice. Approximation techniques applied to the PR are virtually useless if they distort the properties of the co-opetition mechanism. Therefore, sample research questions do not only comprise the adaption of existing techniques to the

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[7] This is the case if the PR payments approximate payments as made by the consulted benchmark ETF-2, which can be seen in detail in the simulation results provided in Section 7.1.

[8] Analogically, service providers may offer lower qualities at constant prices.

PR, but also cover the design of alternative approximation approaches that retain the co-opetition's properties.

A parallelized computation of the PR may yield an alternative to approximation. How can the computation of the power ratio be decomposed into independent sub-units such that the calculation of the payoffs can be distributed, for instance, by reverting to computing services in the cloud (e.g. Amazon EC2)? Thus, an area for further research may be the PR's eligibility for decomposition and ways to distributedly process such computation jobs.

8.3 Complementary Research

This section gives a summary of research directions which are not rated direct extensions to this thesis. They shall rather point the reader to aspects that are complementary to SVNs and the co-opetition mechanism and may thereby be valuable from a broader viewpoint.

Process-oriented service allocation and QoS aggregation

From a customer's perspective, the requested complex service is most probably only a part of a much bigger and more complex business process that depicts an overall value-added process. Within this process, one or more on-demand complex services – for instance, procured via an SVN – may be merged with internally provided services.

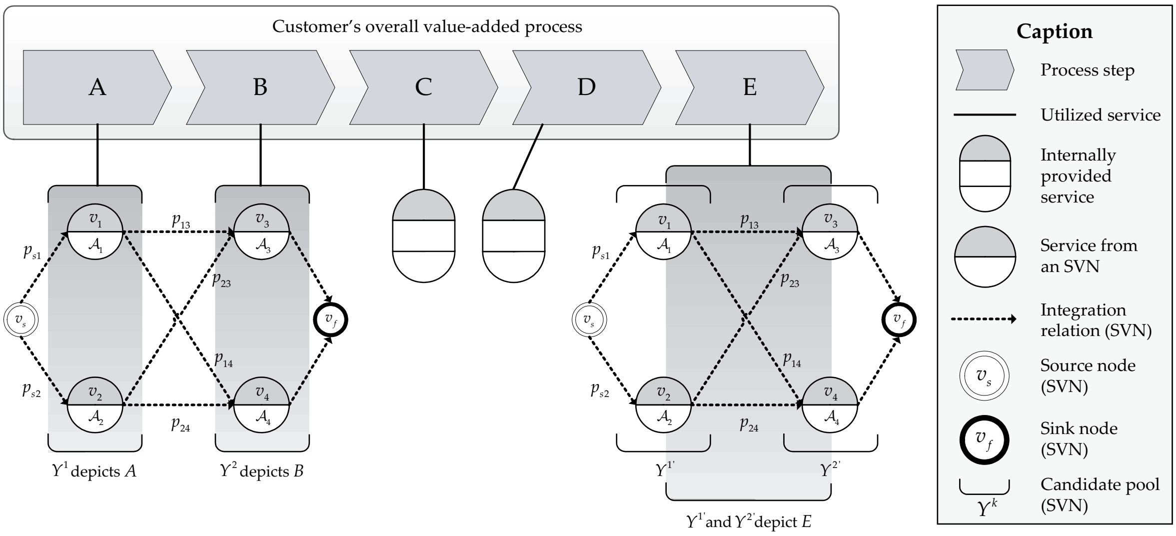

Figure 8.1: Customer's business process including a heterogeneity of invoked services

As depicted in Figure 8.1, the customer's process steps and the complex services as offered in SVNs can be mapped differently. On the one hand, candidate pools in the SVN could fulfill process steps exactly as they are (cp. Y^1 and A, Y^2 and B). On the other hand, they may be available in a more granular fashion, such that, for instance, an SVN including two candidate pools is mapped onto a single step (cp. $Y^{1'}/Y^{2'}$ and E). Further, the example shows a situation in which steps C and D

are accomplished internally. It is obvious that, from the customer's perspective, an aggregation of QoS attributes does not (or not only) matter on the complex service level, as interpreted in this thesis, but rather over the entire value-added process at customer-side, including both external and internal services. Therefore, complementary research questions include the challenge of how to incorporate the whole customer business process into a service request that is only intended to cover a process fragment. That way, QoS is not optimized in terms of the SVN at hand, but with respect to the entire customer process.

In this connection, complementary research questions also deal with a more detailed consideration of the underlying process model. By including different, more detailed process patterns besides service sequences – for instance, loops and parallel or alternative process fragments – the aggregation of QoS attributes complicates [176]: service attributes are subject to a different aggregation logic depending on the underlying process pattern. A simple example is shown in Figure 8.2. The same attribute *maximum downtime (md)* is treated differently in a process fragment including a parallelization of two components (e.g., an *AND Split*) than in a sequential process pattern. While the maximum downtime of the former workflow patterns equals the maximum attribute value of the affected services ($a_1 = \max\{a_4, a_5\}$ and $a_3 = \max\{a_6, a_7\}$), the latter requires the sum operator due to the sequential execution of the services ($a_{agg} = \sum_{i=1}^{3} a_i$).

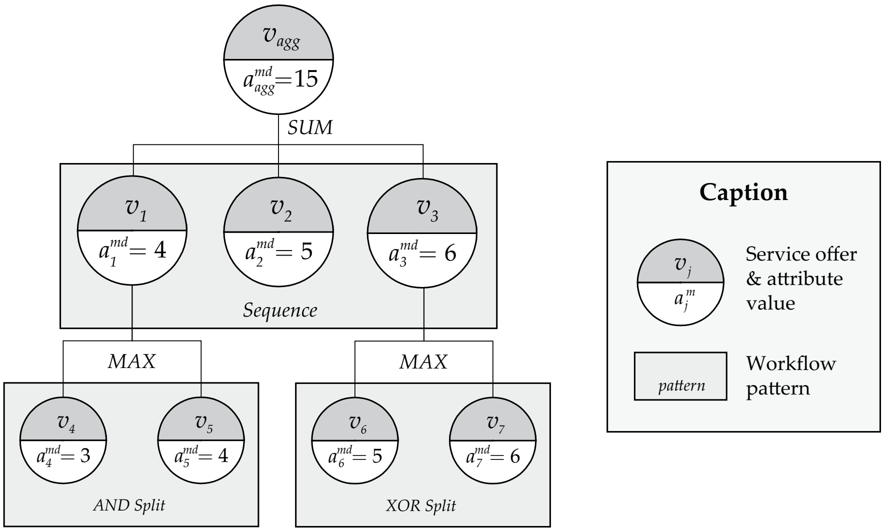

Figure 8.2: Different aggregation operators dependent on the process context

Both the number of possible process fragments and the variety of non-functional service attributes to be included are potentially very high. Van der Aalst [1] showed that each and every workflow pattern can be traced back to a few universally valid basic types of patterns. Is it also possible to classify service attributes by the applicable aggregation operator, subject to them occurring in different process patterns? Can such clustered service quality attributes and aggregation operations be described (for, instance, in an ontology), such that automated aggregation of QoS attributes is facilitated? First approaches to the above-mentioned line of research can be found in Blake and Cummings [44], Unger et al. [319], Knapper et al. [191, 190].

Enforcement of service levels

This field of complementary research is closely related to the one outlined above. It reflects a quite common assumption in applied mechanism design approaches (cp. e.g. [201, 288, 306]): after the mechanism has determined the choice (allocation and payments), the market participants are assumed to adhere to it (cp. Assumption 5.4). This simplifying assumption does always hit reality due to both technical failures and strategic issues. In the work at hand, it is assumed that performance of service providers can effectively be monitored and penalized, if necessary. As soon as the delivery of services moves from "best-effort provisioning" to the provisioning of a guaranteed service quality, monitoring becomes a crucial point of proof for both providers and customers. A first approach to distributed contracting and monitoring from a technical viewpoint has been presented by Spillner et al. [301]. An interesting field of further research is the question of *how* to penalize provider effectively. Can a penalty term be included into the transfer function? Blau et al. [48], Blau [45] present an extension to their complex service auction which compensates customers in case of non- or mal-performance, such that strategic action on provider-side is not beneficial. Rana et al. [269] investigate suitable penalty schemes in a distributed grid environment. If such an enforcement is infeasible, is there a way to include a dedicated attribute, for instance, reputation, into the service's non-functional properties such that mal-performance is sustainably cut back?

Inclusion of services' reputations

Directly building upon the complementary research question raised above, reputation can be represented by aggregating performance of service providers from the trading history. This way, trustworthiness of service providers is indicated and interpreted as expected performance. The latter can be taken into account when deciding upon an actual allocation and its pricing – and thus also impacts future allocation and pricing decisions [142]. Does such a scheme incentivize service providers to not overstate their QoS? In this case, it is not only important to identify suitable aggregation logics to compute the actual reputation "score", but also to put research efforts into determining more sophisticated ways of including such reputation attributes into the co-opetition mechanism. In addition, which is the right type of reputation system to be implemented? First, one could rely on parties rating each other in order to determine the reputation score.[9] However, such user-driven ratings must consider that the service customer will not be able to rate single service components in the majority of cases. Therefore, ratings are likely to take place on a complex service level. Second, if the platform operator imposes a central reputation mechanism based on actual performance, effective monitoring systems are required in order to compare quoted QoS and the quality of actually provisioned services. This option allows for ratings on a component service level, yet brings about additional complexity.

Currently, centralized reputation mechanisms are almost always based on single agents. This circumstance raises another, reciprocal field of complementary research. For instance, Haller [144] presented a stochastic reputation system for virtual

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[9] A detailed listing of current trust and reputation systems based on ratings created by the community (i.e., in the case of this thesis, service customers and providers) can be found in Jøsang et al. [182].

organization managers to identify trusted partners. If such approaches are transferred to a complex service level, that is, situations in which a composition of two or more services are required to offer a value-creating outcome, how can reputation scores be weighted and aggregated in order to obtain a reputation value on complex service level or on a network level? Here, the relative power ratio (cp. Equation 8.2) as a measure that outputs a value representing the percental marginal contribution to the overall network at hand for each service may be consulted as a promising metric [81].

Support for preference elicitation

A common assumption in mechanism design approaches is that agents are always able to express their preferences to the mechanism. However, especially if trading objects expose multiple dimensions – in the co-opetition mechanism's case, QoS attributes – participants find it difficult to actually elicit their preferences and thus, to state their type. In case of complex services, not only multiple heterogenous quality attributes, but also their aggregation over the whole process must be incorporated. Surprisingly, as the elicitation of preferences is more or less a prerequisite of any negotiation situation, and auctions in particular, research on how to design the interface between agents and the mechanism in order to facilitate preference elicitation has received almost no attention so far [294]. A central research question of preference elicitation in mechanisms such as the one at hand can be stated as follows: Is there a simple (and effective) way for participants to extract and express their types correctly? Anandasivam [7] showed that traditional methodologies that have been successfully applied in the field of marketing can generally be applied in the service sector. However, they tend to be complex and time-consuming themselves. For instance, a conjoint analysis approach [138] which asked customers to sort service compositions with a multiplicity of different configurations according to their preferences would be questionable in terms of efficiency. Bichler et al. [40] experimented with user interfaces for the buyer side based on methodologies similar to analytical hierarchical processing (AHP) and multi-attribute utility theory (MAUT) [282, 78].[10] Valuable complementary research efforts may involve a reassessment of such decision analysis approaches applied to complex services, putting forth user interfaces that ease preference elicitation. However, such research needs to tackle the issue that above-mentioned methodologies tend to turn quite complex and tedious with increasing numbers of included service modules, service attributes, and parameterizations thereof.

Revenue considerations under capacity restrictions

By Assumption 5.5, capacity constraints on provider-side are faded out. However, customers are oftentimes not able to accurately foresee their own usage behavior of Web services which leads to the inherent "on-demand characteristic" [26] – at the same time being one of the most striking value propositions of Web services. There-

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[10] Generally, such tool-based approaches are not only able to extract agents' preferences, but also to elicit their utility function. Recall that according to the bidding language presented in Section 5.1.2, customer-stated upper and lower boundaries of attribute values exhibit a linearly coherency. Yet, the co-opetition mechanism is also capable of handling other configurations.

fore, providers' resources might not suffice in peak times to serve all customers that arrive in the SVN while lying idle in other time periods. Complementary research questions may originate from different domains. On the one hand, time series analysis deals with the extraction of usage or demand statistics and patterns, resulting in a more accurate prediction of workloads to support service providers in preparing service delivery by, for instance, having available additional resources in estimated peak times. Research challenges may involve the application of suitable approximation techniques that allow for an appropriate time series analysis in the Web service market.

On the other hand, picking up the very idea of such usage pattern prediction, revenue management approaches add an economic perspective by mapping anticipated customer behavior onto an optimization of resource allocation. How can customers' types and their behavior be anticipated in order to efficiently allocate limited and perishable service capacity? Depending on the actual capacity utilization, should inquiries be declined awaiting a different type of customer that is willing to pay a higher price? Is it profitable to freeze and queue running service instances in favor of high priority inquiries that exhibit a higher willingness to pay? Anandasivam and Neumann [8] show that the Web service market generally differs from traditional revenue management domains such as the airline industry, however, established concepts and methods can generally be adapted. Service value networks may lift these approaches to a higher level: competition between services in identical candidate pools notwithstanding, is there an efficient way to conduct revenue management on the network level, that is, from the platform operator's perspective, and thereby exploit interconnectedness? That way, given the incoming customer requests and the available services, optimization of resources may be transferrable to the overall network. In this context, optimal capacity allocation must take place along complex services, that is, other than in current approaches, the sequence of service modules to be invoked needs to be adhered to.

Extending the power ratio to generic service networks

Based on the constructive definition of services, electronic services, and Web services as presented in Section 2.1, service value networks were defined as being composed of Web services only (cp. Section 2.2). First and foremost, this restriction is founded on two major SVN characteristics that are directly based on distinct Web services properties. Web services' public and well-defined interfaces give rise to automated composition, while their transmission via Web protocols lets the composition take place on a universally accessible network – the Internet.

Promising complementary research includes the transfer of the power ratio to other service domains. While other components of the co-opetition mechanism's social choice may not be suitable to other domains, granting payments to an extended set of service providers falls into place in several scenarios. For instance, critical service processes in the health care domain oftentimes require both readiness to deliver and high availability which could be backed up by substitute services. Making available such buffers, e.g. in hospital processes or in the chain of survival, involves costs and, thus, must be effectively compensated. This work provides a measure, the power ratio, which is designed to account for such a remuneration of alternatives on a process level.

Mobility and transportation is another promising application domain which may allow for an analogous application of the PR: akin to the health care scenario, having available buffers increases the system's robustness against unexpected failures. This is crucial if, for instance, in a logistics scenario, supply is guaranteed at a certain quality level. It is obvious that such extra capacity lies idle if it remains unused. A customer-driven request for a carriage of a defined set of items at a defined quality can be transferred to the SVN perspective as to its layout of paths. The power ratio may be well-suited for determining payments to reward alternative modules for their readiness within this network, thereby ensuring reliability.

Part V

Appendix

Appendix A

Appendix to Part II

A.1 Quality of Service Extensions

As thoroughly discussed by Blau [45], the mere consideration of basic quality attributes may not suffice in practice. More sophisticated QoS characteristics that require additional semantic information, such as for instance, ownership rights or different types of encryption, need to be handled just as well as simple characteristics that can be aggregated via a sum operator.

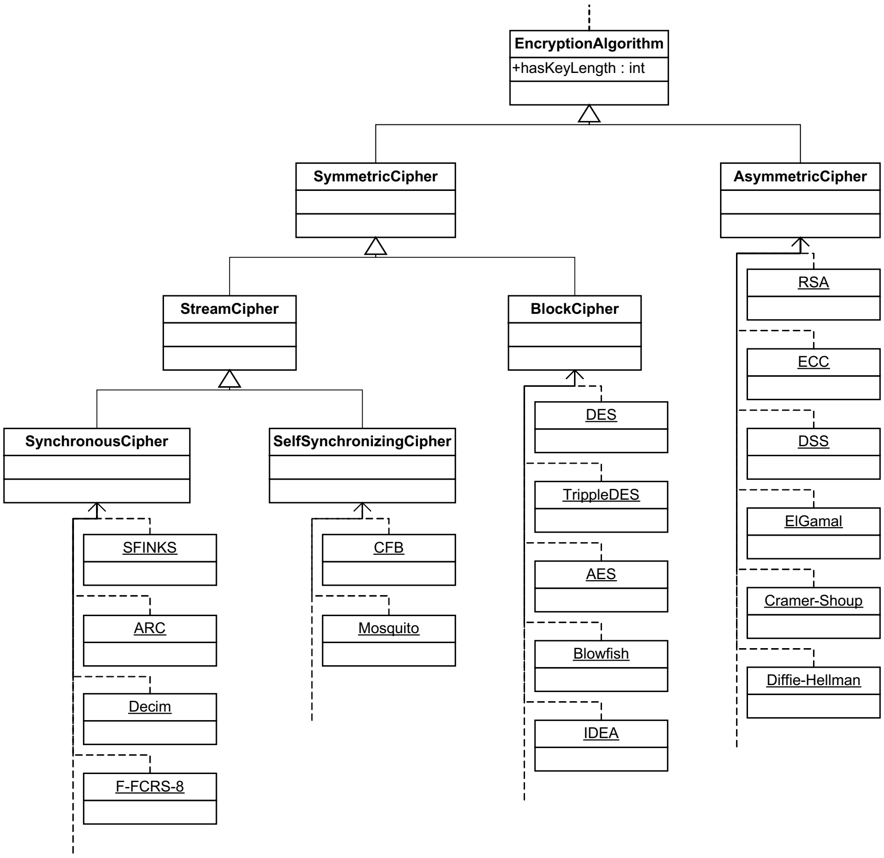


Figure A.1: Security encryption ontology
Blau et al. [48]

Such additional semantic information is usually stored in an ontology [308] which, in turn, requires adequate knowledge representation formalisms, as for instance, the Web Ontology Language (OWL) [218]. In order to tackle complex QoS characteristics, semantic concepts can also be included in the co-opetition mechanism. As exemplified by Blau [45], a customer requirement longing for a distinct encryption type[1] requires *(i)* a Boolean aggregation operator and *(ii)* additional knowledge about how different encryption types can be combined. The latter information can be efficiently stored in an ontology such as the security encryption ontology shown in Figure A.1. An exhaustive numerical example illustrating the capabilities of such QoS extensions in an SVN environment can be found in Blau [45].

A.2 Non-Budget Balanced Variant of the Co-Opetition Mechanism

The allocation function of the co-opetition mechanism includes the assumption that the customer's utility is entirely redistributed to the service providers as the unique source of money flows. In Section 8.2.1, a non-budget balanced alternative is brought up to account for explicit incentives on customer-side. In this variant, $\mathcal{P}_{F^*} = \sum_{e_{ij} \in E(W^*)} p_{ij}$ will be charged to the customer for the allocated complex service F^*.[2]

Therefore, the service customer's utility $\mathcal{U}^{SC}_{F_l}$ when procuring a complex service F_l is assembled by the service configuration-adapted willingness to pay net of the sum of the submitted prices for the edges included in F_l.

$$\mathcal{U}^{SC}_{F_l} = \alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) - \mathcal{P}_{F_l} \tag{A.1}$$

The aggregated service provider utility assembles analogue to Definition 5.3. Let again δ_j denote the monetary surplus that is distributed to v_j. For the reader's convenience, Equation (5.6) is reprinted as Equation (A.2).

$$\mathcal{U}^{SP} = \mathcal{U}^{SP}_{F_l} + \mathcal{U}^{SP}_{\neg F_l} = \sum_{\substack{v_j \in W^*, \\ e_{ij} \in E(W^*)}} \left(p_{ij} - c_{ij} + \delta_j\right) + \sum_{v_j \notin W_l} \delta_j \tag{A.2}$$

Based on Equations (A.1) and (A.2), the actual system's welfare assembles as the sum of $\mathcal{U}^{SC}_{F^*}$, $\mathcal{U}^{SP}_{F^*}$, and the utility of the platform operator $\mathcal{U}^{PO}_{F^*}$ who grants the subsidy with respect to the allocated complex service F^*. As the monetized added value for the customer created by the SVN shall be the amount of money distributed via the power ratio, the welfare $\mathcal{W}^{NB}$ created in this non-budget balanced variant of the co-opetition mechanism equals $\mathcal{W}$:

---

[1] The customer can individually formulate its request via rules that can be interpreted by the ontology.

[2] This section draws on the notation introduced in Section 2.2.3.

$$
\begin{aligned}
\text{(A.3)} \qquad \mathcal{W}^{NB} =& \underbrace{-(\alpha \cdot \mathcal{Q}(A_{F^*}) - \sum_{e_{ij} \in E(W^*)} p_{ij})}_{U^{PO}_{F^*}} + \underbrace{(\alpha \cdot \mathcal{Q}(A_{F^*}) - \sum_{e_{ij} \in E(W^*)} p_{ij})}_{U^{SC}_{F^*}} \\
&\underbrace{+(\alpha \cdot \mathcal{Q}(A_{F^*}) - \sum_{e_{ij} \in E(W^*)} p_{ij}) + (\sum_{e_{ij} \in E(W^*)} p_{ij} - c_{ij})}_{U^{SP}_{F^*}} \\
=&(\alpha \cdot \mathcal{Q}(A_{F^*}) - \sum_{e_{ij} \in E(W^*)} c_{ij}) \\
=&\mathcal{W}
\end{aligned}
$$

Analogue to Equation (5.11), the mechanism operator can calculate the expected welfare $\tilde{\mathcal{W}}^{NB}$ by equating the reported types with the revealed true types, which equals $\tilde{\mathcal{W}}$:

$$
\text{(A.4)} \qquad \tilde{\mathcal{W}}^{NB} = (\alpha \cdot \mathcal{Q}(\mathcal{A}_{F^*}) - \sum_{e_{ij} \in E(W^*)} p_{ij}) = \tilde{\mathcal{W}}
$$

As a result of Equation (A.4), the allocation function $o : \mathcal{B} \times \Theta \rightarrow F$ that chooses the complex service that maximizes the reported system's welfare equals the allocation function as introduced in Definition 5.5, in particular, Equation (5.12):

$$
\begin{aligned}
\text{(A.5)} \qquad o :=& \operatorname*{argmax}_{F_l \in F} \left(\alpha \cdot \mathcal{Q}\left(\mathcal{A}_{F_l}\right) - \sum_{i,j:\ e_{ij} \in E(W^*)} p_{ij} \right) \\
\text{s.t.} \qquad & \mathcal{U}_{F_l} \geq 0 \ \forall \ F_l \in F
\end{aligned}
$$

The basic difference to the allocation function as presented in Section 5.2.2 is that Equation (A.5) does not only maximize the reported welfare, but obviously both the customer utility (cp. Equation A.1) and the aggregated service provider utility (cp. Equation A.2).

A.3 Complexity of the Power Ratio

Mathematical induction is consulted in order to prove the following statement (cp. also Equation 5.25):

$$\sum_{i=1}^{x} \binom{x}{i} = 2^x - 1 \tag{A.6}$$

Basis: Show that the statement holds for $x = 1$.

$$2^1 - 1 = 1 = \binom{1}{1} \tag{A.7}$$

Inductive step: Assume that Equation (A.6) is true for x. It then needs to be shown that the statement also holds for $x + 1$:

$$\begin{aligned}
&\sum_{i=1}^{x+1} \binom{x+1}{i} = \sum_{i=1}^{x} \binom{x+1}{i} + \binom{x+1}{x+1} \\
=&\sum_{i=1}^{x} \binom{x+1}{i} + 1 \overset{(A.9)}{=} \sum_{i=1}^{x} \left(\binom{x}{i} + \binom{x}{i-1} \right) + 1 \\
=&\sum_{i=1}^{x} \binom{x}{i} + \sum_{i=1}^{x} \binom{x}{i-1} + 1 = \sum_{i=1}^{x} \binom{x}{i} + \sum_{j=0}^{x-1} \binom{x}{j} + 1 \\
=&\sum_{i=1}^{x} \binom{x}{i} + \sum_{i=1}^{x} \binom{x}{i} + 1 \overset{(A.6)}{=} 2 \cdot (2^x - 1) + 1 \\
=&2^{x+1} - 2 + 1 = 2^{x+1} - 1
\end{aligned} \tag{A.8}$$

with

$$\binom{x+1}{i+1} = \binom{x}{i} + \binom{x}{i+1} \Leftrightarrow \binom{x+1}{i} = \binom{x}{i-1} + \binom{x}{i} \tag{A.9}$$

Obviously, according to the result from Equation (A.8), Equation (A.6) also holds for $x + 1$. Since the basis and the inductive step can be proved, Equation (A.6) is true for all $x \in \mathbb{N}$.

□

Appendix B

Appendix to Part III

B.1 Network Growth

Table B.1: Average share $|m|_{rel}$ of service providers opting for m^{PRTF} and m^{ETF-1} (3). The numbers do not add up to 100% – the remaining share denotes the state in which service providers are indifferent between choosing m^{PRTF} and m^{ETF-1}.

	$\lvert m\rvert_{rel}$, (2,8)		$\lvert m\rvert_{rel}$, (2,10)		$\lvert m\rvert_{rel}$, (3,5)		$\lvert m\rvert_{rel}$, (3,6)	
	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$
ϱ_1	79.5%	3.56%	82.4%	2.21%	72.6%	10.5%	78.3%	7.80%
ϱ_2	77.8%	13.2%	80.5%	10.6%	68.0%	23.3%	73.5%	19.0%
ϱ_3	65.6%	30.1%	74.2%	21.2%	58.7%	37.6%	62.4%	33.0%
ϱ_4	55.2%	0.61%	49.8%	0.29%	68.8%	4.69%	69.5%	2.26%
ϱ_5	67.5%	2.69%	62.3%	2.30%	69.7%	12.5%	72.9%	8.61%
ϱ_6	66.8%	14.4%	67.7%	9.97%	66.9%	22.7%	70.6%	17.8%
ϱ_7	17.5%	0.00%	13.7%	0.00%	54.8%	1.37%	49.7%	0.14%
ϱ_8	32.0%	0.29%	31.3%	0.00%	63.4%	4.71%	55.9%	1.57%
ϱ_9	47.6%	3.01%	46.1%	1.51%	66.4%	11.0%	60.7%	8.61%

Table B.2: Expected utilities of service provider classes in the PRTF and the ETF-1 market subject to different network configurations (3). * denotes significance at the level of p=0.1, ** denotes significance at the level of p=0.01. AR^{PRTF} stands for attraction rate of the PRTF-based market.

	$\bar{E}(u^m_\varrho)$, (2,8)		$\bar{E}(u^m_\varrho)$, (2,10)		$\bar{E}(u^m_\varrho)$, (3,5)		$\bar{E}(u^m_\varrho)$, (3,6)	
	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$	$PRTF$	$ETF-1$
ϱ_1	0.074**	0.043	0.057**	0.037	0.126**	0.109	0.107*	0.089
ϱ_2	0.138*	0.128	0.114*	0.103	0.194	0.222	0.166	0.194
ϱ_3	0.221	0.290	0.181	0.229	0.276	0.372	0.230	0.312
ϱ_4	0.032**	0.005	0.021**	0.001	0.088**	0.041	0.067**	0.022
ϱ_5	0.060**	0.022	0.042**	0.015	0.140**	0.107	0.109**	0.073
ϱ_6	0.110**	0.086	0.084**	0.065	0.188**	0.169	0.154**	0.135
ϱ_7	0.007**	0.000	0.004**	0.000	0.047**	0.009	0.032**	0.002
ϱ_8	0.014**	0.003	0.008**	0.000	0.081**	0.033	0.048**	0.012
ϱ_9	0.032**	0.014	0.018**	0.006	0.116**	0.073	0.080**	0.045
AR^{PRTF}	88.9%		88.9%		77.8%		77.8%	

B.2 Bidding Strategies

In addition to the data provided in Sections 7.1.2 and 7.1.3, this section includes further statistics and illustrations to back up the results presented in Section 7.1.

B.2.1 Bidding Strategies: Unilateral Manipulation

For each payment rule (PRTF, ETF-1, and ETF-2) and at each manipulation level r, the following Tables B.3 to B.10 outline the mean absolute utilities AU, the mean utility ratio UR of single manipulating service providers, and the standard deviation SD of the mean absolute utility.

Table B.3: Utility of an arbitrary service provider assuming unilateral manipulation in $(2, 3, \alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.017	0.680	0.041	0.015	0.633	0.060	0.021	0.834	0.041
0.95	0.017	0.692	0.042	0.015	0.647	0.060	0.021	0.844	0.041
0.90	0.017	0.708	0.043	0.015	0.663	0.061	0.021	0.857	0.042
0.85	0.018	0.724	0.043	0.016	0.680	0.062	0.022	0.870	0.042
0.80	0.018	0.735	0.044	0.016	0.687	0.062	0.022	0.881	0.042
0.75	0.018	0.750	0.044	0.017	0.722	0.064	0.022	0.896	0.042
0.70	0.019	0.770	0.045	0.017	0.742	0.064	0.023	0.913	0.043
0.65	0.019	0.781	0.045	0.018	0.753	0.065	0.023	0.919	0.043
0.60	0.019	0.793	0.045	0.018	0.760	0.065	0.023	0.926	0.042
0.55	0.020	0.805	0.045	0.018	0.775	0.065	0.023	0.935	0.042
0.50	0.020	0.820	0.045	0.018	0.792	0.065	0.024	0.946	0.042
0.45	0.021	0.839	0.046	0.019	0.816	0.067	0.024	0.958	0.042
0.40	0.021	0.854	0.046	0.019	0.832	0.067	0.024	0.965	0.042
0.35	0.021	0.874	0.046	0.020	0.845	0.067	0.024	0.976	0.042
0.30	0.022	0.891	0.046	0.020	0.858	0.067	0.025	0.985	0.041
0.25	0.022	0.916	0.046	0.021	0.892	0.068	0.025	0.998	0.041
0.20	0.023	0.942	0.047	0.022	0.929	0.069	0.025	1.010	0.041
0.15	0.024	0.966	0.047	0.022	0.957	0.069	0.026	1.021**	0.040
0.10	0.024	0.983	0.046	0.023	0.983	0.069	0.026	1.022**	0.040
0.05	0.024	0.995	0.046	0.023	0.998	0.069	0.026	1.020**	0.039
0.00	0.025	1.000	0.000	0.023	1.000	0.000	0.025	1.000	0.000
-0.05	0.024	0.992	0.045	0.023	0.990	0.068	0.024	0.962	0.038
-0.10	0.024	0.959	0.046	0.022	0.951	0.068	0.022	0.891	0.039
-0.15	0.022	0.878	0.048	0.021	0.902	0.070	0.019	0.770	0.042
-0.20	0.018	0.737	0.053	0.018	0.781	0.073	0.015	0.579	0.049
-0.25	0.014	0.563	0.060	0.014	0.614	0.078	0.009	0.339	0.058
-0.30	0.008	0.319	0.070	0.009	0.378	0.085	0.001	0.025	0.070
-0.35	0.001	0.028	0.081	0.002	0.096	0.094	-0.009	-0.350	0.084
-0.40	-0.009	-0.347	0.094	-0.006	-0.267	0.105	-0.021	-0.820	0.100
-0.45	-0.021	-0.840	0.111	-0.017	-0.750	0.121	-0.035	-1.413	0.118
-0.50	-0.035	-1.406	0.128	-0.031	-1.308	0.137	-0.052	-2.093	0.137
-0.55	-0.049	-2.004	0.145	-0.045	-1.917	0.154	-0.071	-2.819	0.156
-0.60	-0.065	-2.644	0.161	-0.060	-2.587	0.170	-0.090	-3.598	0.174
-0.65	-0.081	-3.314	0.177	-0.077	-3.279	0.186	-0.111	-4.418	0.192
-0.70	-0.101	-4.099	0.194	-0.096	-4.105	0.203	-0.134	-5.364	0.211
-0.75	-0.121	-4.924	0.210	-0.116	-4.971	0.220	-0.160	-6.363	0.228
-0.80	-0.148	-6.025	0.228	-0.142	-6.101	0.239	-0.192	-7.646	0.247

Table B.3: Utility of an arbitrary service provider assuming unilateral manipulation in $(2, 3, \alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
-0.85	-0.167	-6.790	0.240	-0.162	-6.931	0.252	-0.216	-8.608	0.261
-0.90	-0.192	-7.821	0.255	-0.186	-7.988	0.268	-0.247	-9.844	0.275
-0.95	-0.216	-8.810	0.268	-0.211	-9.040	0.283	-0.277	-11.047	0.289

Table B.4: Utility of an arbitrary service provider assuming unilateral manipulation in $(2, 4, \alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.068	0.687	0.072	0.055	0.559	0.166	0.089	0.901	0.070
0.95	0.069	0.694	0.072	0.055	0.560	0.166	0.090	0.906	0.070
0.90	0.069	0.701	0.072	0.055	0.566	0.167	0.090	0.913	0.069
0.85	0.070	0.710	0.072	0.056	0.567	0.167	0.091	0.917	0.069
0.80	0.071	0.717	0.072	0.055	0.566	0.166	0.091	0.921	0.068
0.75	0.073	0.733	0.073	0.057	0.587	0.168	0.093	0.933	0.068
0.70	0.074	0.746	0.074	0.062	0.629	0.176	0.093	0.942	0.068
0.65	0.075	0.755	0.073	0.061	0.627	0.175	0.094	0.948	0.067
0.60	0.076	0.765	0.073	0.062	0.631	0.175	0.095	0.954	0.066
0.55	0.077	0.776	0.073	0.062	0.629	0.175	0.095	0.958	0.065
0.50	0.078	0.793	0.073	0.064	0.652	0.177	0.096	0.970	0.064
0.45	0.080	0.811	0.074	0.067	0.685	0.182	0.097	0.982	0.064
0.40	0.082	0.829	0.075	0.069	0.700	0.183	0.098	0.991	0.064
0.35	0.084	0.851	0.076	0.075	0.765	0.190	0.100	1.003	0.063
0.30	0.086	0.865	0.075	0.075	0.762	0.190	0.099	1.003*	0.062
0.25	0.087	0.882	0.075	0.076	0.779	0.190	0.100	1.005*	0.061
0.20	0.090	0.913	0.076	0.080	0.813	0.192	0.101	1.019**	0.061
0.15	0.092	0.932	0.075	0.081	0.826	0.193	0.101	1.016**	0.060
0.10	0.095	0.957	0.074	0.083	0.852	0.194	0.101	1.018**	0.058
0.05	0.097	0.982	0.074	0.090	0.923	0.199	0.101	1.015**	0.057
0.00	0.099	1.000	0.000	0.098	1.000	0.000	0.099	1.000	0.000
-0.05	0.100	1.010**	0.073	0.106	1.082**	0.209	0.096	0.972	0.058
-0.10	0.098	0.991	0.073	0.111	1.133**	0.211	0.092	0.930	0.061
-0.15	0.098	0.988	0.076	0.115	1.175**	0.211	0.085	0.856	0.069
-0.20	0.092	0.929	0.084	0.120	1.231**	0.213	0.073	0.739	0.083
-0.25	0.085	0.863	0.095	0.118	1.207**	0.213	0.060	0.606	0.100
-0.30	0.074	0.747	0.110	0.119	1.217**	0.220	0.041	0.417	0.121
-0.35	0.064	0.647	0.122	0.114	1.170**	0.223	0.024	0.238	0.140
-0.40	0.049	0.496	0.139	0.108	1.102**	0.227	0.000	0.003	0.162
-0.45	0.030	0.302	0.155	0.108	1.106**	0.240	-0.028	-0.281	0.182
-0.50	0.018	0.179	0.167	0.099	1.008	0.245	-0.049	-0.498	0.199
-0.55	0.005	0.050	0.177	0.096	0.980	0.253	-0.072	-0.726	0.215
-0.60	-0.014	-0.146	0.190	0.087	0.894	0.263	-0.101	-1.023	0.232
-0.65	-0.029	-0.294	0.203	0.077	0.788	0.273	-0.127	-1.277	0.248
-0.70	-0.048	-0.481	0.214	0.067	0.687	0.284	-0.156	-1.571	0.263
-0.75	-0.061	-0.619	0.224	0.059	0.602	0.294	-0.180	-1.820	0.278
-0.80	-0.076	-0.769	0.232	0.050	0.510	0.302	-0.206	-2.081	0.292
-0.85	-0.090	-0.912	0.239	0.044	0.455	0.313	-0.232	-2.337	0.303
-0.90	-0.107	-1.084	0.244	0.037	0.383	0.323	-0.260	-2.624	0.314
-0.95	-0.122	-1.230	0.251	0.027	0.274	0.331	-0.286	-2.886	0.325

Table B.5: Utility of an arbitrary service provider assuming unilateral manipulation in $(3, 2, \alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			EFT-1			ETF-2		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.005	0.859	0.026	0.005	0.894	0.030	0.006	0.975	0.025
0.95	0.006	0.881	0.027	0.005	0.919	0.030	0.006	0.997	0.025
0.90	0.006	0.887	0.027	0.006	0.921	0.030	0.006	1.002	0.025
0.85	0.006	0.891	0.026	0.005	0.920	0.030	0.006	1.007	0.025
0.80	0.006	0.896	0.026	0.006	0.921	0.030	0.007	1.011	0.024
0.75	0.006	0.925	0.027	0.006	0.948	0.030	0.007	1.035*	0.025
0.70	0.006	0.941	0.027	0.006	0.970	0.030	0.007	1.054*	0.025
0.65	0.006	0.948	0.027	0.006	0.977	0.030	0.007	1.057*	0.025
0.60	0.006	0.949	0.026	0.006	0.971	0.030	0.007	1.058**	0.024
0.55	0.006	0.956	0.026	0.006	0.971	0.030	0.007	1.062**	0.024
0.50	0.006	0.956	0.026	0.006	0.964	0.029	0.007	1.060**	0.024
0.45	0.006	0.962	0.026	0.006	0.973	0.029	0.007	1.063**	0.024
0.40	0.006	0.976	0.026	0.006	0.989	0.029	0.007	1.070**	0.023
0.35	0.006	1.000	0.026	0.006	1.014	0.029	0.007	1.084**	0.023
0.30	0.006	1.018*	0.026	0.006	1.044*	0.029	0.007	1.092**	0.023
0.25	0.007	1.029**	0.026	0.006	1.048**	0.029	0.007	1.094**	0.023
0.20	0.007	1.041**	0.025	0.006	1.056**	0.029	0.007	1.095**	0.022
0.15	0.007	1.038**	0.025	0.006	1.048**	0.028	0.007	1.081**	0.022
0.10	0.007	1.032**	0.025	0.006	1.036**	0.028	0.007	1.064**	0.021
0.05	0.006	1.023**	0.024	0.006	1.025**	0.027	0.007	1.043**	0.021
0.00	0.006	1.000	0.000	0.006	1.000	0.000	0.006	1.000	0.000
-0.05	0.006	0.952	0.023	0.006	0.972	0.026	0.006	0.937	0.019
-0.10	0.006	0.875	0.023	0.005	0.880	0.026	0.005	0.839	0.019
-0.15	0.005	0.777	0.024	0.005	0.779	0.027	0.005	0.714	0.020
-0.20	0.004	0.572	0.027	0.003	0.559	0.029	0.003	0.477	0.024
-0.25	0.002	0.241	0.032	0.001	0.233	0.033	0.001	0.113	0.030
-0.30	-0.001	-0.098	0.037	-0.001	-0.110	0.038	-0.002	-0.265	0.036
-0.35	-0.003	-0.542	0.044	-0.003	-0.564	0.045	-0.005	-0.760	0.045
-0.40	-0.007	-1.144	0.054	-0.007	-1.192	0.055	-0.009	-1.412	0.055
-0.45	-0.012	-1.905	0.066	-0.012	-2.034	0.067	-0.014	-2.237	0.069
-0.50	-0.018	-2.837	0.080	-0.018	-3.048	0.081	-0.021	-3.243	0.083
-0.55	-0.025	-3.921	0.094	-0.025	-4.196	0.095	-0.028	-4.417	0.098
-0.60	-0.033	-5.144	0.109	-0.033	-5.503	0.110	-0.037	-5.733	0.114
-0.65	-0.041	-6.446	0.123	-0.041	-6.895	0.125	-0.046	-7.140	0.130
-0.70	-0.050	-7.950	0.139	-0.051	-8.509	0.141	-0.056	-8.764	0.147
-0.75	-0.063	-9.913	0.159	-0.064	-10.637	0.161	-0.070	-10.849	0.167
-0.80	-0.077	-12.102	0.180	-0.078	-13.022	0.182	-0.085	-13.186	0.189
-0.85	-0.095	-15.040	0.203	-0.096	-16.139	0.206	-0.105	-16.276	0.213
-0.90	-0.113	-17.891	0.224	-0.115	-19.192	0.228	-0.124	-19.290	0.236
-0.95	-0.130	-20.495	0.243	-0.132	-22.038	0.248	-0.142	-22.088	0.256

Table B.6: Utility of an arbitrary service provider assuming unilateral manipulation in $(3, 2, \alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			EFT-1			ETF-2		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.244	0.831	0.150	0.172	0.583	0.310	0.292	0.994	0.137
0.95	0.246	0.837	0.150	0.173	0.584	0.310	0.292	0.994	0.136
0.90	0.248	0.845	0.149	0.174	0.589	0.310	0.293	0.997	0.136
0.85	0.251	0.855	0.150	0.178	0.602	0.314	0.294	1.001	0.136
0.80	0.253	0.862	0.149	0.179	0.606	0.314	0.294	1.002	0.135

Table B.6: Utility of an arbitrary service provider assuming unilateral manipulation in $(3, 2, \alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
0.75	0.255	0.869	0.149	0.181	0.612	0.315	0.295	1.004*	0.134
0.70	0.258	0.880	0.149	0.185	0.627	0.318	0.296	1.008**	0.134
0.65	0.262	0.891	0.149	0.190	0.642	0.321	0.298	1.013**	0.134
0.60	0.265	0.902	0.149	0.194	0.658	0.324	0.299	1.016**	0.134
0.55	0.268	0.911	0.149	0.199	0.673	0.326	0.299	1.019**	0.133
0.50	0.271	0.922	0.148	0.203	0.688	0.328	0.300	1.022**	0.133
0.45	0.275	0.936	0.149	0.211	0.715	0.332	0.302	1.028**	0.133
0.40	0.277	0.945	0.147	0.216	0.730	0.333	0.302	1.029**	0.132
0.35	0.281	0.957	0.146	0.222	0.751	0.335	0.303	1.032**	0.130
0.30	0.285	0.970	0.145	0.233	0.789	0.340	0.305	1.037**	0.130
0.25	0.287	0.979	0.144	0.240	0.813	0.341	0.304	1.036**	0.128
0.20	0.289	0.986	0.142	0.247	0.838	0.343	0.304	1.033**	0.127
0.15	0.292	0.994	0.140	0.256	0.868	0.343	0.303	1.030**	0.125
0.10	0.293	0.999	0.138	0.265	0.896	0.343	0.301	1.024**	0.124
0.05	0.295	1.003**	0.135	0.283	0.959	0.343	0.299	1.017**	0.122
0.00	0.294	1.000	0.000	0.295	1.000	0.000	0.294	1.000	0.000
-0.05	0.291	0.990	0.134	0.306	1.035**	0.338	0.287	0.975	0.125
-0.10	0.285	0.970	0.136	0.317	1.073**	0.334	0.276	0.940	0.130
-0.15	0.277	0.944	0.139	0.324	1.095**	0.329	0.264	0.898	0.137
-0.20	0.268	0.913	0.145	0.327	1.108**	0.324	0.250	0.849	0.146
-0.25	0.257	0.875	0.153	0.327	1.106**	0.320	0.233	0.793	0.157
-0.30	0.243	0.827	0.162	0.326	1.105**	0.316	0.213	0.726	0.170
-0.35	0.227	0.773	0.172	0.325	1.100**	0.313	0.192	0.652	0.183
-0.40	0.210	0.714	0.183	0.323	1.094**	0.312	0.168	0.572	0.197
-0.45	0.194	0.659	0.193	0.318	1.076**	0.313	0.146	0.497	0.209
-0.50	0.176	0.598	0.204	0.306	1.037**	0.315	0.122	0.414	0.224
-0.55	0.156	0.532	0.215	0.296	1.003	0.317	0.096	0.326	0.236
-0.60	0.140	0.477	0.223	0.284	0.962	0.320	0.073	0.249	0.248
-0.65	0.124	0.421	0.232	0.272	0.922	0.324	0.050	0.170	0.260
-0.70	0.105	0.357	0.241	0.261	0.885	0.328	0.024	0.083	0.271
-0.75	0.086	0.294	0.250	0.248	0.839	0.334	-0.001	-0.003	0.283
-0.80	0.069	0.236	0.257	0.235	0.797	0.340	-0.025	-0.084	0.293
-0.85	0.052	0.178	0.264	0.223	0.756	0.346	-0.049	-0.165	0.303
-0.90	0.034	0.114	0.271	0.208	0.703	0.353	-0.074	-0.252	0.313
-0.95	0.017	0.056	0.277	0.194	0.656	0.359	-0.098	-0.334	0.323

Table B.7: Utility of an arbitrary service provider assuming unilateral manipulation in $(3, 3, \alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.038	0.735	0.058	0.035	0.676	0.099	0.048	0.927	0.055
0.95	0.038	0.741	0.058	0.036	0.681	0.099	0.048	0.932	0.055
0.90	0.039	0.753	0.059	0.036	0.695	0.100	0.049	0.942	0.055
0.85	0.039	0.762	0.059	0.037	0.703	0.100	0.049	0.950	0.055
0.80	0.040	0.771	0.059	0.037	0.711	0.100	0.050	0.958	0.055
0.75	0.040	0.781	0.060	0.038	0.719	0.101	0.050	0.968	0.055
0.70	0.041	0.788	0.059	0.038	0.721	0.101	0.050	0.971	0.054
0.65	0.041	0.802	0.060	0.038	0.735	0.101	0.051	0.983	0.055
0.60	0.042	0.811	0.060	0.039	0.744	0.102	0.051	0.987	0.054
0.55	0.043	0.825	0.060	0.039	0.754	0.102	0.052	0.997	0.054

Table B.7: Utility of an arbitrary service provider assuming unilateral manipulation in $(3,3,\alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
0.50	0.043	0.837	0.061	0.040	0.767	0.103	0.052	1.005	0.054
0.45	0.044	0.850	0.061	0.041	0.777	0.103	0.052	1.009*	0.054
0.40	0.045	0.872	0.062	0.042	0.806	0.105	0.053	1.024**	0.054
0.35	0.046	0.889	0.062	0.043	0.817	0.106	0.053	1.029**	0.054
0.30	0.047	0.902	0.062	0.043	0.825	0.106	0.053	1.031**	0.053
0.25	0.048	0.927	0.062	0.045	0.852	0.107	0.054	1.044**	0.053
0.20	0.049	0.949	0.062	0.046	0.874	0.107	0.054	1.049**	0.052
0.15	0.050	0.971	0.062	0.048	0.909	0.108	0.055	1.052**	0.051
0.10	0.051	0.985	0.061	0.049	0.938	0.109	0.054	1.042**	0.050
0.05	0.052	0.997	0.060	0.050	0.961	0.109	0.053	1.027**	0.049
0.00	0.052	1.000	0.000	0.052	1.000	0.000	0.052	1.000	0.000
-0.05	0.051	0.985	0.059	0.053	1.010	0.110	0.049	0.949	0.048
-0.10	0.049	0.945	0.060	0.053	1.009	0.110	0.045	0.865	0.051
-0.15	0.045	0.872	0.063	0.052	0.995	0.112	0.039	0.744	0.057
-0.20	0.039	0.758	0.071	0.047	0.907	0.114	0.030	0.571	0.068
-0.25	0.032	0.613	0.080	0.042	0.794	0.118	0.019	0.362	0.081
-0.30	0.022	0.423	0.092	0.033	0.632	0.124	0.005	0.100	0.097
-0.35	0.012	0.223	0.103	0.025	0.472	0.132	-0.009	-0.181	0.113
-0.40	-0.001	-0.018	0.117	0.014	0.268	0.142	-0.026	-0.508	0.130
-0.45	-0.014	-0.276	0.131	0.001	0.019	0.153	-0.045	-0.860	0.149
-0.50	-0.029	-0.569	0.146	-0.013	-0.252	0.165	-0.065	-1.254	0.167
-0.55	-0.047	-0.915	0.161	-0.030	-0.579	0.179	-0.088	-1.705	0.185
-0.60	-0.067	-1.291	0.177	-0.048	-0.908	0.194	-0.114	-2.195	0.203
-0.65	-0.086	-1.659	0.192	-0.065	-1.249	0.210	-0.139	-2.683	0.220
-0.70	-0.107	-2.079	0.206	-0.087	-1.657	0.225	-0.167	-3.228	0.237
-0.75	-0.127	-2.453	0.219	-0.106	-2.034	0.239	-0.193	-3.732	0.253
-0.80	-0.148	-2.872	0.233	-0.128	-2.457	0.254	-0.222	-4.286	0.268
-0.85	-0.170	-3.291	0.245	-0.150	-2.875	0.268	-0.251	-4.845	0.283
-0.90	-0.192	-3.717	0.255	-0.173	-3.298	0.281	-0.281	-5.417	0.296
-0.95	-0.211	-4.081	0.266	-0.192	-3.675	0.294	-0.307	-5.931	0.309

Table B.8: Utility of an arbitrary service provider assuming unilateral manipulation in $(3,4,\alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.032	0.750	0.046	0.030	0.729	0.091	0.040	0.930	0.041
0.95	0.032	0.754	0.046	0.031	0.734	0.092	0.040	0.932	0.041
0.90	0.032	0.758	0.046	0.031	0.735	0.092	0.040	0.936	0.041
0.85	0.033	0.767	0.046	0.031	0.744	0.093	0.040	0.945	0.041
0.80	0.033	0.774	0.046	0.031	0.751	0.093	0.040	0.950	0.041
0.75	0.033	0.780	0.046	0.032	0.756	0.094	0.041	0.955	0.041
0.70	0.034	0.790	0.047	0.032	0.765	0.094	0.041	0.961	0.041
0.65	0.034	0.798	0.047	0.032	0.770	0.094	0.041	0.967	0.041
0.60	0.034	0.809	0.048	0.032	0.778	0.095	0.041	0.975	0.041
0.55	0.035	0.821	0.048	0.033	0.788	0.095	0.042	0.984	0.041
0.50	0.036	0.837	0.049	0.034	0.808	0.096	0.042	0.995	0.041
0.45	0.036	0.849	0.049	0.034	0.818	0.096	0.043	1.000	0.041
0.40	0.037	0.860	0.049	0.034	0.823	0.097	0.043	1.004	0.041
0.35	0.037	0.877	0.049	0.035	0.843	0.098	0.043	1.012**	0.041
0.30	0.038	0.893	0.050	0.036	0.860	0.098	0.043	1.019**	0.041

Table B.8: Utility of an arbitrary service provider assuming unilateral manipulation in $(3, 4, \alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
0.25	0.039	0.910	0.050	0.036	0.874	0.099	0.044	1.025**	0.040
0.20	0.040	0.930	0.050	0.037	0.894	0.099	0.044	1.029**	0.039
0.15	0.041	0.957	0.050	0.039	0.940	0.101	0.044	1.037**	0.039
0.10	0.042	0.974	0.049	0.040	0.960	0.101	0.044	1.032**	0.038
0.05	0.042	0.992	0.049	0.041	0.983	0.101	0.044	1.024**	0.037
0.00	0.043	1.000	0.000	0.042	1.000	0.000	0.043	1.000	0.000
-0.05	0.042	0.996	0.048	0.043	1.033**	0.102	0.041	0.959	0.037
-0.10	0.041	0.969	0.049	0.044	1.045**	0.103	0.038	0.884	0.040
-0.15	0.039	0.914	0.052	0.043	1.031*	0.103	0.033	0.774	0.046
-0.20	0.035	0.822	0.058	0.041	0.991	0.105	0.026	0.618	0.056
-0.25	0.029	0.670	0.068	0.037	0.895	0.109	0.017	0.390	0.070
-0.30	0.021	0.492	0.078	0.033	0.784	0.114	0.005	0.127	0.086
-0.35	0.009	0.214	0.094	0.023	0.547	0.123	-0.011	-0.250	0.106
-0.40	-0.003	-0.063	0.109	0.013	0.304	0.132	-0.027	-0.638	0.124
-0.45	-0.017	-0.397	0.126	0.000	-0.005	0.146	-0.046	-1.094	0.145
-0.50	-0.034	-0.801	0.144	-0.016	-0.377	0.161	-0.069	-1.630	0.166
-0.55	-0.051	-1.193	0.160	-0.031	-0.753	0.175	-0.092	-2.166	0.185
-0.60	-0.069	-1.613	0.175	-0.048	-1.152	0.190	-0.116	-2.740	0.204
-0.65	-0.090	-2.114	0.191	-0.067	-1.606	0.206	-0.145	-3.405	0.223
-0.70	-0.112	-2.633	0.206	-0.088	-2.118	0.222	-0.174	-4.098	0.241
-0.75	-0.133	-3.123	0.219	-0.109	-2.609	0.236	-0.203	-4.772	0.258
-0.80	-0.154	-3.624	0.231	-0.129	-3.100	0.251	-0.232	-5.466	0.273
-0.85	-0.175	-4.104	0.242	-0.150	-3.591	0.265	-0.261	-6.146	0.287
-0.90	-0.195	-4.570	0.252	-0.170	-4.077	0.278	-0.290	-6.817	0.301
-0.95	-0.216	-5.080	0.262	-0.191	-4.585	0.290	-0.321	-7.540	0.313

Table B.9: Utility of an arbitrary service provider assuming unilateral manipulation in $(4, 3, \alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.001	0.942	0.010	0.001	0.847	0.010	0.002	1.129*	0.009
0.95	0.001	0.938	0.009	0.001	0.837	0.010	0.002	1.117*	0.009
0.90	0.001	0.940	0.009	0.001	0.834	0.010	0.002	1.113*	0.009
0.85	0.001	0.952	0.009	0.001	0.844	0.010	0.002	1.117*	0.009
0.80	0.001	0.947	0.009	0.001	0.833	0.010	0.002	1.110*	0.009
0.75	0.001	0.943	0.009	0.001	0.822	0.010	0.002	1.102*	0.008
0.70	0.001	0.939	0.009	0.001	0.811	0.010	0.002	1.098*	0.008
0.65	0.001	0.976	0.009	0.001	0.902	0.010	0.002	1.130**	0.008
0.60	0.001	0.972	0.009	0.001	0.888	0.010	0.002	1.123**	0.008
0.55	0.001	0.967	0.009	0.001	0.874	0.010	0.002	1.107**	0.008
0.50	0.001	0.964	0.009	0.001	0.860	0.010	0.002	1.095**	0.008
0.45	0.001	0.983	0.009	0.001	0.870	0.010	0.002	1.108**	0.008
0.40	0.001	0.989	0.009	0.001	0.865	0.010	0.002	1.108**	0.008
0.35	0.001	0.985	0.008	0.001	0.848	0.009	0.002	1.095**	0.007
0.30	0.001	0.981	0.008	0.001	0.831	0.009	0.002	1.076**	0.007
0.25	0.001	0.978	0.008	0.001	0.815	0.009	0.001	1.057**	0.007
0.20	0.001	1.022	0.009	0.001	0.866	0.009	0.002	1.098**	0.007
0.15	0.001	1.021*	0.008	0.001	0.851	0.009	0.002	1.078**	0.007
0.10	0.001	1.010	0.008	0.001	0.822	0.009	0.001	1.049**	0.007
0.05	0.001	1.015**	0.008	0.001	1.007	0.010	0.001	1.038**	0.007

Table B.9: Utility of an arbitrary service provider assuming unilateral manipulation in $(4, 3, \alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			EFT-1			ETF-2		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
0.00	0.001	1.000	0.000	0.001	1.000	0.000	0.001	1.000	0.000
-0.05	0.001	0.953	0.008	0.001	0.953	0.010	0.001	0.926	0.006
-0.10	0.001	0.862	0.008	0.001	0.962	0.010	0.001	0.805	0.006
-0.15	0.001	0.776	0.008	0.001	0.952	0.011	0.001	0.690	0.007
-0.20	0.001	0.617	0.009	0.001	0.784	0.011	0.001	0.493	0.008
-0.25	0.001	0.384	0.011	0.001	0.521	0.012	0.000	0.210	0.010
-0.30	0.000	0.241	0.012	0.000	0.327	0.013	0.000	0.004	0.012
-0.35	0.000	0.013	0.014	0.000	0.034	0.015	0.000	-0.289	0.015
-0.40	-0.001	-0.597	0.019	-0.001	-0.533	0.019	-0.001	-0.979	0.019
-0.45	-0.002	-1.633	0.026	-0.002	-1.653	0.026	-0.003	-2.119	0.027
-0.50	-0.003	-2.250	0.030	-0.003	-2.342	0.031	-0.004	-2.846	0.032
-0.55	-0.005	-3.534	0.038	-0.005	-3.727	0.038	-0.006	-4.277	0.040
-0.60	-0.007	-4.816	0.046	-0.007	-5.187	0.046	-0.008	-5.728	0.048
-0.65	-0.009	-6.410	0.055	-0.009	-6.979	0.055	-0.011	-7.514	0.058
-0.70	-0.013	-8.938	0.068	-0.013	-9.667	0.068	-0.015	-10.289	0.071
-0.75	-0.018	-12.632	0.085	-0.018	-13.769	0.085	-0.020	-14.298	0.089
-0.80	-0.025	-17.296	0.105	-0.025	-18.891	0.106	-0.027	-19.330	0.109
-0.85	-0.035	-23.877	0.127	-0.035	-26.155	0.128	-0.037	-26.386	0.132
-0.90	-0.044	-30.227	0.148	-0.044	-33.188	0.149	-0.047	-33.255	0.153
-0.95	-0.056	-38.130	0.171	-0.056	-41.956	0.172	-0.059	-41.777	0.177

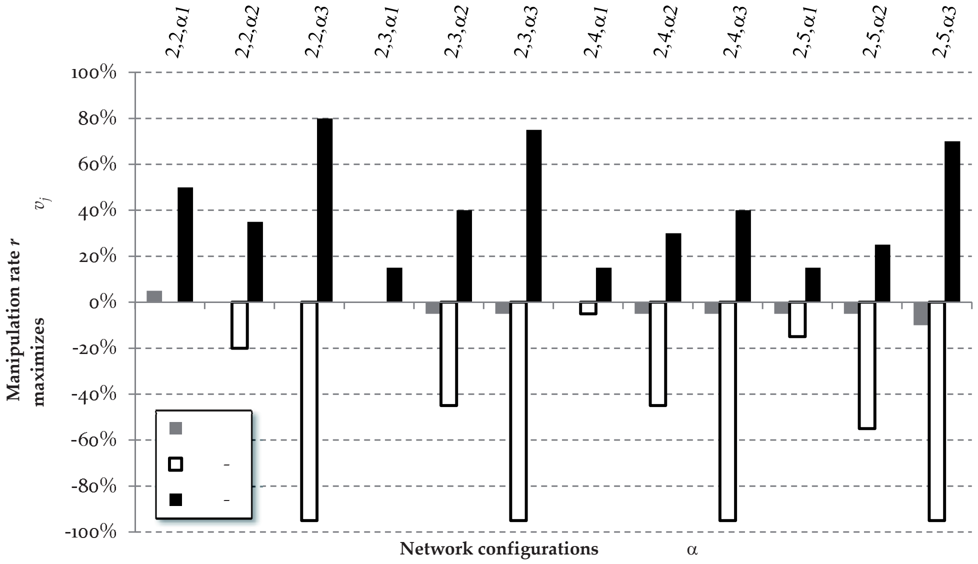
Table B.10: Utility of an arbitrary service provider assuming unilateral manipulation in $(4, 3, \alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			EFT-1			ETF-2		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.096	0.807	0.093	0.078	0.651	0.180	0.119	0.988	0.074
0.95	0.098	0.817	0.094	0.080	0.662	0.182	0.119	0.994	0.075
0.90	0.099	0.826	0.095	0.080	0.667	0.182	0.120	0.999	0.075
0.85	0.100	0.834	0.095	0.081	0.673	0.183	0.120	1.003	0.075
0.80	0.101	0.844	0.096	0.082	0.683	0.184	0.121	1.008*	0.075
0.75	0.102	0.852	0.096	0.083	0.691	0.185	0.122	1.012**	0.074
0.70	0.103	0.863	0.096	0.085	0.701	0.186	0.122	1.017**	0.074
0.65	0.105	0.875	0.097	0.086	0.715	0.188	0.123	1.023**	0.074
0.60	0.106	0.886	0.097	0.087	0.724	0.189	0.123	1.026**	0.074
0.55	0.107	0.894	0.097	0.088	0.732	0.189	0.123	1.027**	0.073
0.50	0.108	0.905	0.097	0.090	0.746	0.191	0.124	1.030**	0.073
0.45	0.109	0.916	0.097	0.093	0.769	0.193	0.124	1.034**	0.072
0.40	0.111	0.928	0.097	0.094	0.782	0.194	0.125	1.037**	0.072
0.35	0.112	0.939	0.097	0.096	0.800	0.195	0.125	1.038**	0.071
0.30	0.114	0.954	0.097	0.100	0.828	0.197	0.125	1.043**	0.070
0.25	0.115	0.964	0.096	0.101	0.841	0.198	0.125	1.041**	0.069
0.20	0.117	0.975	0.096	0.104	0.865	0.199	0.125	1.040**	0.068
0.15	0.118	0.986	0.095	0.107	0.891	0.199	0.125	1.037**	0.067
0.10	0.119	0.997	0.094	0.113	0.935	0.201	0.124	1.033**	0.065
0.05	0.120	1.001*	0.093	0.117	0.970	0.203	0.123	1.020**	0.064
0.00	0.119	1.000	0.000	0.120	1.000	0.000	0.120	1.000	0.000
-0.05	0.118	0.988	0.091	0.125	1.033**	0.203	0.116	0.967	0.065
-0.10	0.115	0.962	0.092	0.128	1.061**	0.202	0.110	0.917	0.069
-0.15	0.110	0.921	0.095	0.129	1.070**	0.201	0.102	0.849	0.077
-0.20	0.103	0.863	0.100	0.128	1.065**	0.199	0.091	0.761	0.087

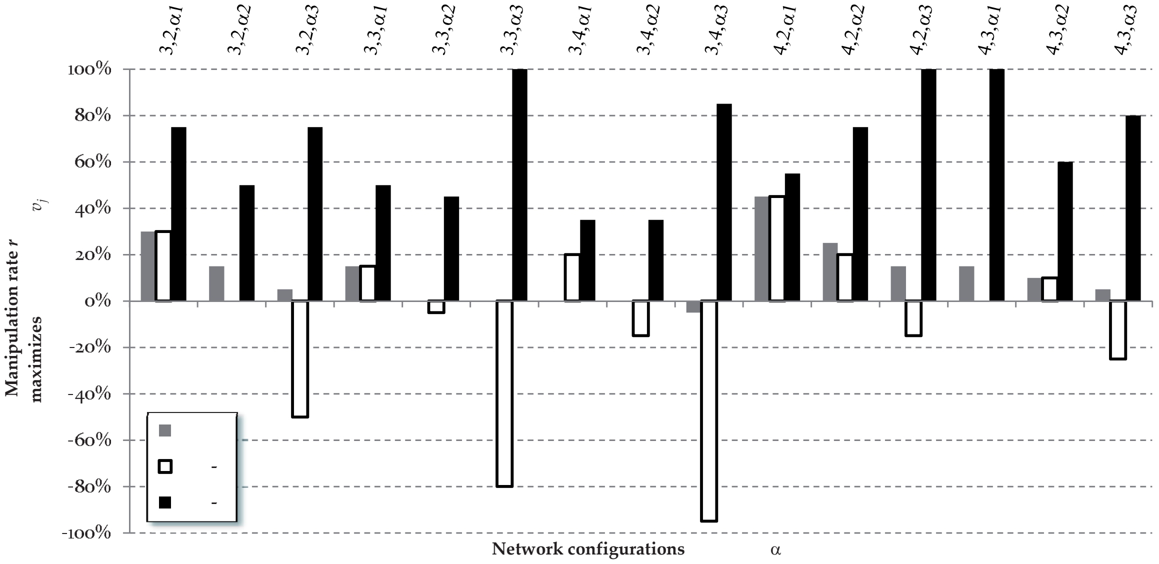
Table B.10: Utility of an arbitrary service provider assuming unilateral manipulation in $(4,3,\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
-0.25	0.094	0.785	0.109	0.127	1.053**	0.199	0.078	0.650	0.101
-0.30	0.081	0.677	0.120	0.122	1.013	0.200	0.061	0.506	0.118
-0.35	0.067	0.563	0.132	0.116	0.961	0.201	0.043	0.354	0.135
-0.40	0.051	0.425	0.147	0.108	0.892	0.205	0.021	0.174	0.153
-0.45	0.034	0.283	0.160	0.098	0.811	0.210	-0.001	-0.012	0.171
-0.50	0.015	0.127	0.174	0.085	0.709	0.216	-0.026	-0.214	0.188
-0.55	-0.003	-0.029	0.188	0.072	0.594	0.223	-0.050	-0.418	0.206
-0.60	-0.025	-0.213	0.201	0.058	0.480	0.233	-0.078	-0.652	0.222
-0.65	-0.047	-0.390	0.213	0.042	0.348	0.242	-0.106	-0.882	0.238
-0.70	-0.068	-0.566	0.225	0.026	0.214	0.252	-0.134	-1.113	0.253
-0.75	-0.087	-0.730	0.237	0.009	0.076	0.262	-0.160	-1.331	0.268
-0.80	-0.108	-0.901	0.248	-0.009	-0.073	0.273	-0.187	-1.559	0.282
-0.85	-0.128	-1.067	0.258	-0.026	-0.214	0.283	-0.214	-1.782	0.295
-0.90	-0.149	-1.250	0.266	-0.044	-0.363	0.294	-0.243	-2.023	0.307
-0.95	-0.170	-1.427	0.275	-0.063	-0.519	0.304	-0.271	-2.259	0.319

Figure B.1 illustrates of manipulation rates that *maximize* the service providers' utilities in different configurations. Moreover, Figure B.2 plots the relative utility gain (or loss) from manipulation by $x\%$ with any other service provider reporting its true type for an additional set of four network configurations where deviation is only profitable in a very limited extent applying the PRTF. Figure B.3 shows another four configurations that allow for profitable manipulation of price bids to a larger extent.

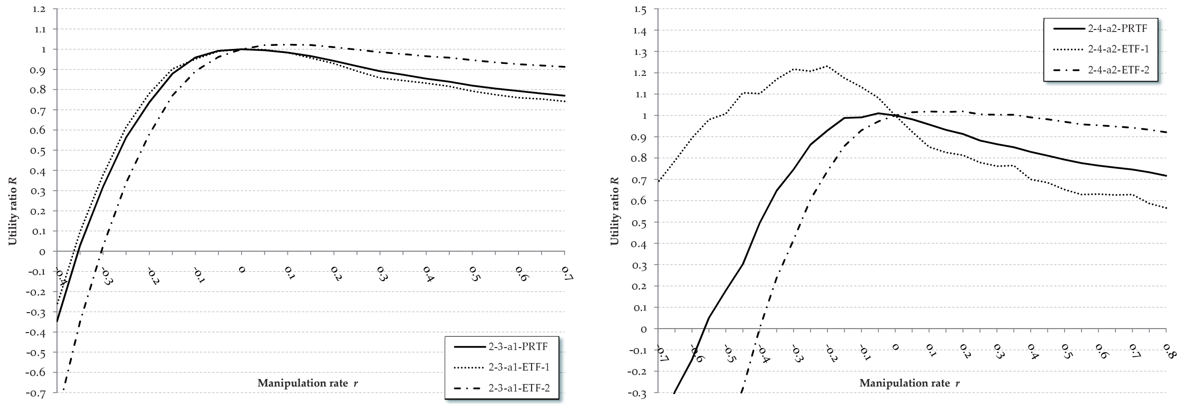


(a) Network configurations with $|Y| = 2$

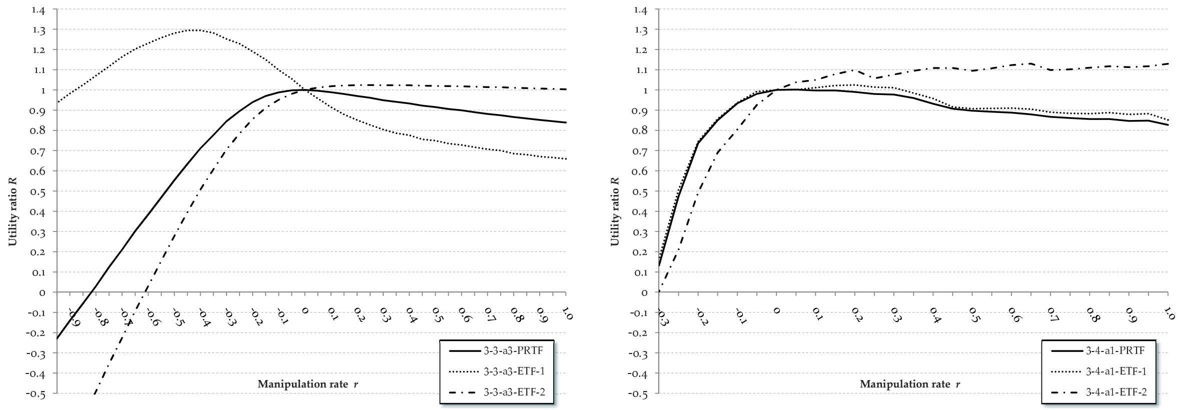


(b) Network configurations with $|Y| = \{3,4\}$

Figure B.1: Manipulation rate that maximizes a service provider's utility assuming unilateral deviation

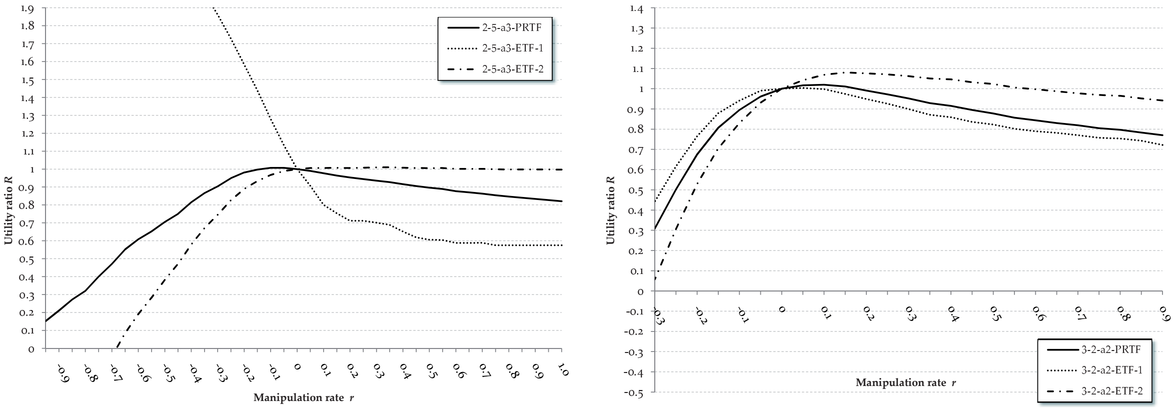


(a) Utility ratios in $(2,3,\alpha_1)$ **(b)** Utility ratios in $(2,4,\alpha_2)$



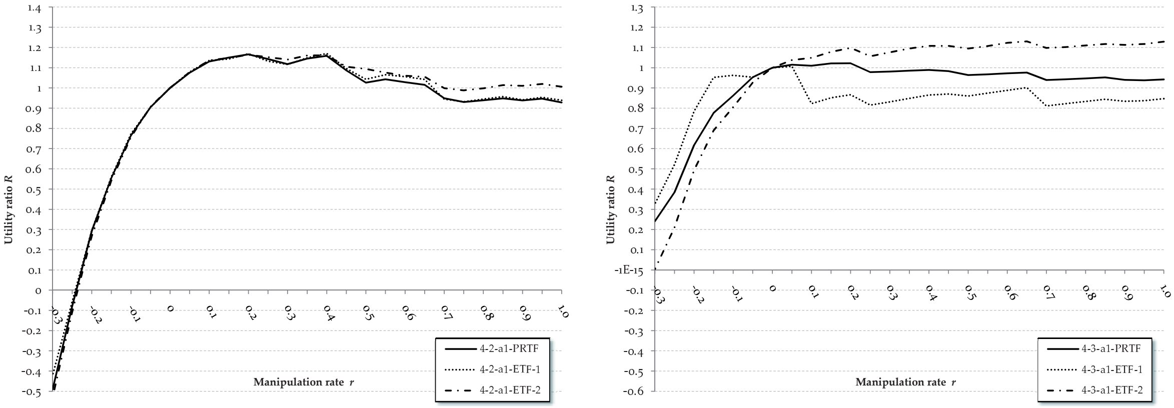
(c) Utility ratios in $(3,3,\alpha_3)$ **(d)** Utility ratios in $(3,4,\alpha_1)$

Figure B.2: Utility ratios of different manipulation rates applying unilateral strategies (selected configurations): Deviation is only profitable in a negligible range in PRTF



(a) Utility ratios in $(2,5,\alpha_3)$

(b) Utility ratios in $(3,2,\alpha_2)$



(c) Utility ratios in $(4,2,\alpha_1)$

(d) Utility ratios in $(4,3,\alpha_1)$

Figure B.3: Utility ratios of different manipulation rates applying unilateral strategies (selected configurations): The PRTF allows for more severe profitable deviation

B.2.2 Symmetric Manipulation

For each payment rule (PRTF, ETF-1, and ETF-2) and at each manipulation level r, the following Tables B.12 to B.14 outline the mean absolute utilities AU, the mean utility ratio UR of single manipulating service providers, and the standard deviation SD of the mean absolute utility. Recall that in a symmetric manipulation scenario, all service providers manipulate their price bid by x%.

Table B.11: Utility of an arbitrary service provider assuming symmetric manipulation in $(2,3,\alpha_1)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	AU	UR	SD	AU	UR	SD	AU	UR	SD
1.00	0.021	0.708	0.066	0.020	0.699	0.078	0.020	0.724	0.059
0.95	0.021	0.714	0.066	0.021	0.706	0.078	0.021	0.732	0.058
0.90	0.021	0.724	0.065	0.021	0.718	0.078	0.021	0.742	0.057
0.85	0.021	0.732	0.065	0.021	0.726	0.078	0.021	0.753	0.057
0.80	0.021	0.739	0.064	0.021	0.734	0.078	0.021	0.762	0.056
0.75	0.022	0.755	0.064	0.022	0.750	0.079	0.022	0.778	0.056
0.70	0.022	0.771	0.064	0.022	0.766	0.079	0.022	0.794	0.056
0.65	0.023	0.791	0.064	0.023	0.787	0.080	0.023	0.814	0.055
0.60	0.024	0.816	0.064	0.024	0.811	0.080	0.024	0.836	0.055
0.55	0.024	0.826	0.064	0.024	0.822	0.080	0.024	0.848	0.054
0.50	0.024	0.843	0.063	0.025	0.838	0.080	0.024	0.863	0.054
0.45	0.025	0.865	0.063	0.025	0.862	0.081	0.025	0.883	0.053
0.40	0.026	0.881	0.062	0.026	0.877	0.081	0.025	0.895	0.052
0.35	0.026	0.900	0.061	0.026	0.897	0.081	0.026	0.915	0.051
0.30	0.027	0.920	0.060	0.027	0.917	0.081	0.026	0.934	0.050
0.25	0.027	0.939	0.059	0.027	0.936	0.080	0.027	0.952	0.048
0.20	0.028	0.953	0.057	0.028	0.952	0.080	0.027	0.968	0.047
0.15	0.028	0.975	0.056	0.028	0.974	0.080	0.028	0.993	0.045
0.10	0.029	0.991	0.054	0.029	0.989	0.080	0.028	0.999	0.044
0.05	0.029	0.999	0.053	0.029	0.997	0.080	0.028	1.004	0.042
0.00	0.029	1.000	0.000	0.029	1.000	0.000	0.028	1.000	0.000
-0.05	0.029	0.993	0.050	0.029	0.995	0.080	0.028	0.998	0.041
-0.10	0.028	0.975	0.050	0.029	0.980	0.080	0.028	0.984	0.042
-0.15	0.028	0.949	0.050	0.028	0.956	0.081	0.027	0.956	0.045
-0.20	0.026	0.910	0.053	0.027	0.919	0.083	0.026	0.918	0.050
-0.25	0.024	0.839	0.058	0.025	0.851	0.086	0.024	0.847	0.057
-0.30	0.022	0.771	0.064	0.023	0.784	0.090	0.022	0.789	0.066
-0.35	0.020	0.680	0.073	0.020	0.693	0.095	0.020	0.698	0.077
-0.40	0.016	0.554	0.085	0.017	0.569	0.102	0.016	0.568	0.091
-0.45	0.012	0.430	0.098	0.013	0.449	0.109	0.012	0.442	0.105
-0.50	0.008	0.283	0.112	0.009	0.306	0.118	0.008	0.294	0.120
-0.55	0.005	0.158	0.127	0.005	0.183	0.126	0.005	0.166	0.135
-0.60	0.001	0.028	0.142	0.002	0.054	0.134	0.001	0.027	0.150
-0.65	-0.001	-0.040	0.155	0.000	-0.011	0.140	-0.001	-0.045	0.164
-0.70	-0.002	-0.063	0.167	-0.001	-0.029	0.144	-0.002	-0.069	0.175
-0.75	-0.002	-0.070	0.179	-0.001	-0.031	0.147	-0.002	-0.076	0.185
-0.80	-0.002	-0.077	0.191	-0.001	-0.033	0.150	-0.002	-0.082	0.196
-0.85	-0.002	-0.084	0.203	-0.001	-0.035	0.153	-0.003	-0.089	0.207
-0.90	-0.003	-0.091	0.215	-0.001	-0.037	0.156	-0.003	-0.095	0.217
-0.95	-0.003	-0.098	0.227	-0.001	-0.040	0.160	-0.003	-0.102	0.228

Table B.12: Utility of an arbitrary service provider assuming symmetric manipulation in $(2,5,\alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.058	0.740	0.136	0.058	0.722	0.186	0.058	0.748	0.115
0.95	0.060	0.768	0.137	0.060	0.750	0.189	0.061	0.776	0.117
0.90	0.062	0.795	0.138	0.062	0.777	0.191	0.063	0.802	0.117
0.85	0.063	0.812	0.136	0.063	0.794	0.192	0.064	0.819	0.116
0.80	0.065	0.830	0.134	0.065	0.812	0.192	0.065	0.836	0.113
0.75	0.067	0.855	0.133	0.067	0.838	0.193	0.067	0.860	0.112
0.70	0.068	0.879	0.130	0.069	0.862	0.194	0.069	0.881	0.109
0.65	0.070	0.896	0.127	0.070	0.880	0.194	0.070	0.899	0.106
0.60	0.071	0.916	0.124	0.072	0.902	0.194	0.072	0.920	0.103
0.55	0.072	0.930	0.120	0.073	0.916	0.194	0.073	0.933	0.098
0.50	0.073	0.938	0.115	0.074	0.926	0.193	0.073	0.940	0.093
0.45	0.074	0.950	0.111	0.075	0.939	0.193	0.074	0.952	0.088
0.40	0.074	0.956	0.105	0.076	0.946	0.192	0.075	0.956	0.082
0.35	0.075	0.964	0.100	0.076	0.956	0.191	0.075	0.966	0.077
0.30	0.076	0.974	0.095	0.077	0.968	0.191	0.076	0.979	0.071
0.25	0.076	0.982	0.090	0.078	0.976	0.190	0.077	0.986	0.066
0.20	0.077	0.989	0.084	0.079	0.985	0.190	0.077	0.993	0.060
0.15	0.078	0.997	0.079	0.079	0.994	0.189	0.078	1.000	0.055
0.10	0.078	1.000	0.073	0.080	0.997	0.189	0.078	1.001	0.051
0.05	0.078	1.001	0.068	0.080	1.000	0.189	0.078	1.002	0.048
0.00	0.078	1.000	0.000	0.080	1.000	0.000	0.078	1.000	0.000
-0.05	0.078	0.997	0.061	0.080	0.999	0.189	0.078	0.998	0.047
-0.10	0.077	0.995	0.060	0.080	0.998	0.189	0.078	0.993	0.050
-0.15	0.077	0.991	0.060	0.080	0.997	0.189	0.077	0.989	0.055
-0.20	0.077	0.986	0.062	0.079	0.994	0.190	0.077	0.985	0.061
-0.25	0.076	0.981	0.066	0.079	0.991	0.191	0.076	0.980	0.068
-0.30	0.076	0.976	0.072	0.079	0.988	0.192	0.076	0.975	0.075
-0.35	0.076	0.970	0.079	0.079	0.984	0.193	0.076	0.969	0.084
-0.40	0.075	0.967	0.086	0.079	0.982	0.194	0.075	0.965	0.092
-0.45	0.075	0.965	0.094	0.079	0.982	0.195	0.075	0.963	0.101
-0.50	0.075	0.963	0.103	0.078	0.982	0.196	0.075	0.961	0.109
-0.55	0.075	0.961	0.112	0.078	0.982	0.198	0.075	0.959	0.118
-0.60	0.075	0.960	0.121	0.078	0.982	0.199	0.075	0.957	0.127
-0.65	0.075	0.958	0.131	0.078	0.982	0.200	0.075	0.956	0.136
-0.70	0.074	0.956	0.140	0.078	0.982	0.202	0.074	0.954	0.146
-0.75	0.074	0.954	0.150	0.078	0.982	0.204	0.074	0.952	0.155
-0.80	0.074	0.952	0.160	0.078	0.982	0.206	0.074	0.950	0.164
-0.85	0.074	0.950	0.171	0.078	0.982	0.207	0.074	0.948	0.173
-0.90	0.074	0.948	0.181	0.078	0.982	0.209	0.074	0.946	0.183
-0.95	0.074	0.946	0.191	0.078	0.982	0.212	0.074	0.944	0.192

Table B.13: Utility of an arbitrary service provider assuming symmetric manipulation in $(3,3,\alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.028	0.533	0.097	0.028	0.533	0.109	0.028	0.527	0.085
0.95	0.029	0.556	0.097	0.029	0.555	0.110	0.029	0.550	0.085
0.90	0.031	0.586	0.098	0.031	0.585	0.112	0.031	0.580	0.086
0.85	0.032	0.612	0.099	0.032	0.612	0.113	0.032	0.605	0.086
0.80	0.033	0.633	0.098	0.033	0.633	0.114	0.033	0.630	0.086

Table B.13: Utility of an arbitrary service provider assuming symmetric manipulation in $(3,3,\alpha_2)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
0.75	0.034	0.654	0.097	0.034	0.653	0.114	0.034	0.648	0.084
0.70	0.035	0.672	0.096	0.035	0.671	0.114	0.035	0.665	0.082
0.65	0.036	0.692	0.095	0.036	0.691	0.114	0.036	0.687	0.081
0.60	0.038	0.727	0.094	0.038	0.727	0.115	0.038	0.724	0.080
0.55	0.040	0.759	0.093	0.040	0.758	0.115	0.040	0.756	0.079
0.50	0.042	0.795	0.092	0.042	0.795	0.115	0.042	0.793	0.077
0.45	0.044	0.835	0.091	0.044	0.833	0.116	0.044	0.832	0.076
0.40	0.045	0.859	0.088	0.045	0.857	0.115	0.045	0.854	0.073
0.35	0.046	0.879	0.085	0.046	0.876	0.115	0.046	0.873	0.070
0.30	0.048	0.910	0.083	0.048	0.907	0.114	0.048	0.903	0.067
0.25	0.049	0.933	0.079	0.049	0.929	0.114	0.049	0.925	0.063
0.20	0.050	0.957	0.076	0.050	0.952	0.113	0.050	0.950	0.059
0.15	0.052	0.980	0.072	0.051	0.975	0.112	0.051	0.973	0.056
0.10	0.052	0.993	0.068	0.052	0.989	0.112	0.052	0.988	0.052
0.05	0.053	1.000	0.064	0.052	0.998	0.111	0.052	0.996	0.049
0.00	0.053	1.000	0.000	0.053	1.000	0.000	0.053	1.000	0.000
-0.05	0.052	0.995	0.059	0.052	0.997	0.111	0.052	0.997	0.049
-0.10	0.052	0.986	0.058	0.052	0.989	0.112	0.052	0.987	0.052
-0.15	0.051	0.972	0.060	0.051	0.976	0.113	0.051	0.972	0.057
-0.20	0.050	0.955	0.063	0.051	0.961	0.115	0.050	0.953	0.065
-0.25	0.049	0.938	0.069	0.050	0.945	0.117	0.049	0.934	0.073
-0.30	0.048	0.916	0.077	0.049	0.926	0.120	0.048	0.914	0.083
-0.35	0.047	0.891	0.086	0.047	0.902	0.123	0.047	0.889	0.094
-0.40	0.046	0.875	0.096	0.047	0.887	0.126	0.046	0.874	0.104
-0.45	0.045	0.855	0.107	0.046	0.869	0.130	0.045	0.856	0.115
-0.50	0.044	0.842	0.118	0.045	0.858	0.134	0.044	0.842	0.126
-0.55	0.044	0.840	0.128	0.045	0.857	0.137	0.044	0.841	0.136
-0.60	0.044	0.839	0.139	0.045	0.857	0.140	0.044	0.839	0.147
-0.65	0.044	0.837	0.150	0.045	0.857	0.144	0.044	0.838	0.157
-0.70	0.044	0.835	0.161	0.045	0.856	0.147	0.044	0.836	0.167
-0.75	0.044	0.834	0.172	0.045	0.856	0.151	0.044	0.835	0.178
-0.80	0.044	0.832	0.184	0.045	0.855	0.155	0.044	0.833	0.189
-0.85	0.044	0.831	0.196	0.045	0.855	0.159	0.044	0.832	0.199
-0.90	0.044	0.829	0.208	0.045	0.854	0.163	0.044	0.830	0.210
-0.95	0.044	0.827	0.220	0.045	0.854	0.168	0.044	0.828	0.221

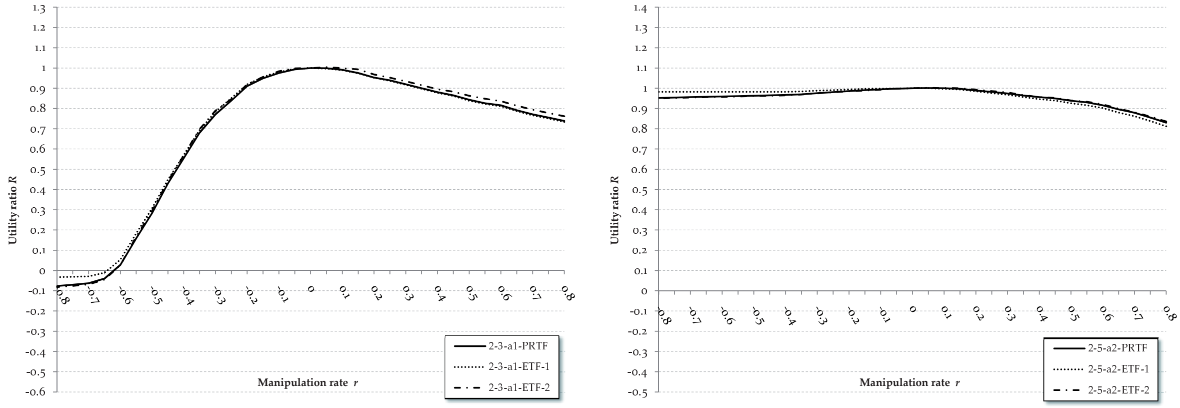
Table B.14: Utility of an arbitrary service provider assuming symmetric manipulation in $(2,2,\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
1.00	0.535	0.968	0.378	0.542	0.963	0.626	0.536	0.969	0.321
0.95	0.539	0.974	0.366	0.545	0.969	0.624	0.539	0.975	0.310
0.90	0.541	0.978	0.354	0.547	0.973	0.622	0.542	0.979	0.299
0.85	0.542	0.980	0.343	0.549	0.976	0.620	0.543	0.981	0.289
0.80	0.544	0.983	0.331	0.551	0.979	0.618	0.545	0.985	0.278
0.75	0.547	0.988	0.318	0.554	0.984	0.616	0.547	0.989	0.266
0.70	0.548	0.991	0.306	0.555	0.987	0.614	0.549	0.992	0.256
0.65	0.550	0.994	0.294	0.557	0.990	0.612	0.550	0.994	0.245
0.60	0.551	0.996	0.283	0.558	0.992	0.611	0.551	0.996	0.236
0.55	0.551	0.997	0.271	0.559	0.994	0.610	0.552	0.997	0.227

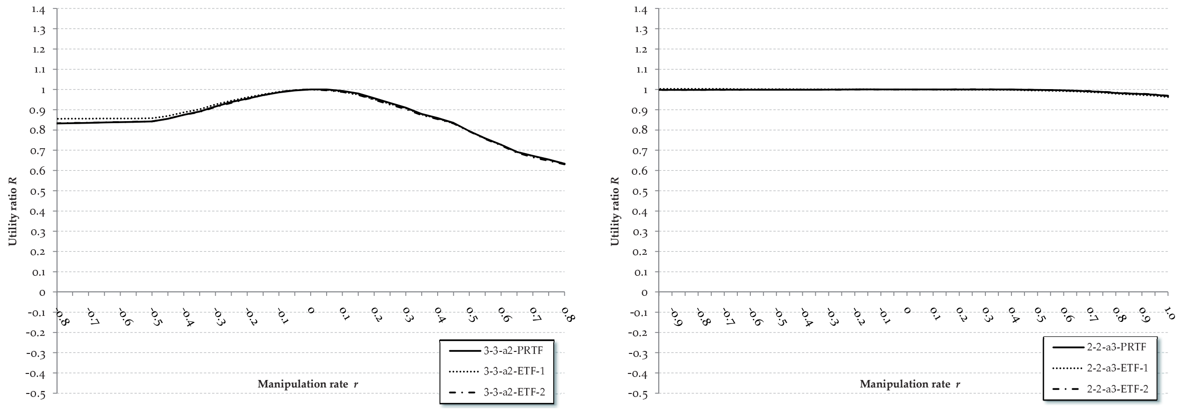
Table B.14: Utility of an arbitrary service provider assuming symmetric manipulation in $(2,2,\alpha_3)$. * denotes significance at the level of $p = 0.1$ and ** at $p = 0.01$.

	PRTF			**EFT-1**			**ETF-2**		
r	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*	*AU*	*UR*	*SD*
0.50	0.552	0.998	0.261	0.560	0.995	0.609	0.552	0.998	0.218
0.45	0.553	0.999	0.250	0.560	0.996	0.608	0.553	0.999	0.210
0.40	0.553	1.000	0.240	0.561	0.998	0.607	0.553	1.000	0.202
0.35	0.553	1.000	0.230	0.562	0.998	0.606	0.554	1.000	0.196
0.30	0.553	1.000	0.221	0.562	0.999	0.606	0.554	1.001	0.190
0.25	0.553	1.000	0.213	0.562	0.999	0.605	0.554	1.001	0.185
0.20	0.553	1.000	0.205	0.562	0.999	0.605	0.554	1.001	0.181
0.15	0.553	1.000	0.199	0.562	0.999	0.605	0.554	1.000	0.178
0.10	0.553	1.000	0.193	0.562	1.000	0.605	0.554	1.000	0.176
0.05	0.553	1.000	0.188	0.562	1.000	0.605	0.553	1.000	0.174
0.00	0.553	1.000	0.000	0.563	1.000	0.000	0.553	1.000	0.000
-0.05	0.553	1.000	0.182	0.563	1.000	0.605	0.553	1.000	0.175
-0.10	0.553	1.000	0.181	0.563	1.000	0.605	0.553	1.000	0.176
-0.15	0.553	1.000	0.181	0.563	1.001	0.605	0.553	1.000	0.179
-0.20	0.553	1.000	0.182	0.563	1.001	0.606	0.553	1.000	0.182
-0.25	0.553	1.000	0.184	0.563	1.001	0.606	0.553	0.999	0.186
-0.30	0.553	0.999	0.187	0.563	1.001	0.607	0.553	0.999	0.192
-0.35	0.553	0.999	0.192	0.563	1.001	0.608	0.553	0.999	0.197
-0.40	0.553	0.999	0.197	0.563	1.001	0.608	0.553	0.999	0.204
-0.45	0.553	0.999	0.203	0.564	1.002	0.609	0.553	0.999	0.211
-0.50	0.553	0.999	0.211	0.564	1.002	0.610	0.553	0.999	0.218
-0.55	0.553	0.999	0.219	0.564	1.002	0.611	0.553	0.999	0.226
-0.60	0.553	0.999	0.227	0.564	1.002	0.612	0.553	0.999	0.235
-0.65	0.553	0.999	0.237	0.564	1.002	0.613	0.553	0.998	0.244
-0.70	0.552	0.999	0.246	0.564	1.003	0.614	0.553	0.998	0.253
-0.75	0.552	0.999	0.257	0.564	1.003	0.615	0.552	0.998	0.262
-0.80	0.552	0.998	0.267	0.564	1.003	0.617	0.552	0.998	0.272
-0.85	0.552	0.998	0.279	0.564	1.003	0.618	0.552	0.998	0.282
-0.90	0.552	0.998	0.290	0.564	1.003	0.620	0.552	0.998	0.292
-0.95	0.552	0.998	0.302	0.565	1.003	0.621	0.552	0.998	0.303

Figure B.4 illustrates the results of Tables B.11 to B.14 by showing the trend of the utility ratios at different manipulation rates.



(a) Utility ratios in $(2,3,\alpha_1)$ **(b)** Utility ratios in $(2,5,\alpha_2)$



(c) Utility ratios in $(3,3,\alpha_2)$ **(d)** Utility ratios in $(2,2,\alpha_3)$

Figure B.4: Utility ratios of different manipulation rates applying symmetric strategies (selected configurations) (2)

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