New types of resource issues in open distributed systems: an agency theory modelling approach

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Abstract

This paper investigates a new class of resource problems in emerging *open* distributed systems. The openness, which includes open access to the system and interworking across organisational boundaries brings a new dimension to the interactions of players in such systems. Due to geographical, administrative and other boundaries, the players can take advantage of private information, behave opportunistically, or take advantage of the actions of others, in striving to achieve their own objectives. These issues can lead to a major problem of *uncertainty* of service delivery, which needs to be taken into account when designing mechanisms to assure the optimal balance for all of the benefits of new systems. This particularly applies to a large set of information services which can be regarded as non-standard and which can involve significant complexity. Experience from the real world suggests that the inherent uncertainty of such services can normally be reduced by means of contracts. To design contracts which will govern service delivery in the presence of uncertainty, we propose the use of the theory of games of asymmetric information, in particular, the *principal-agent model,* which is an important ingredient of economic *agency theory* (AT*)* [22], [40]. We show how the problem of service delivery in open distributed systems can be formulated and solved in an agency setting and illustrate this with an example of a trading service.

Keywords: Agency Theory, Open Distributed Systems, Quality of Service, Resource Sharing

1 Introduction

The proliferation of new telecommunications and computing technologies and their rapid decrease in cost have induced important changes in the area of distributed processing: a trend towards *open* distributed systems (ODSs). This is evident in a number of related research and commercial initiatives such as TINA [4], ANSA [1], OMG's CORBA [32], OSF's DCE [36], as well as in the work jointly carried out by ISO and ITU on the standardisation of Open Distributed Processing (ODP) [17]. Two important objectives of an ODS are:

- to make the numerous benefits of distributed systems (e.g. increased availability, performance, decentralised management) accessible to a wider user community,
- to provide an effective sharing and an efficient utilisation of information services as well as computational, communication and other resources, across organisational boundaries.

These goals are of interest for consumers who capitalise on new technologies to achieve critical missions for their enterprises; providers who see their opportunities to extend or diversify potential markets; and regulators who need to assure that the benefits of new technologies are evenly spread across society. With these goals, ODSs set a number of new targets such as:

- *open access* for information services to the community at large,
- capability for *interworking* within and across organisational boundaries,
- support for the simultaneous existence of information services of *highly differentiated* types; this implies different performance requirements,
- incorporation of different levels of *Quality of Service (QoS)*[1]; this is particularly relevant for multi-attribute type of services,

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[1] In order to have a general, service-independent definition of QoS, we adopt an economic-driven definition [3], i.e. QoS represents a set of quality requirements which are expressed in terms of quantities of service characteristics that directly impact with the utility functions of users.

- a *cooperative* and *competitive* environment in which services are provided by different service providers, solely or in cooperation with others,
- the formation of a *global market* for information services in which users play a dominant role.

However, in order to reach these targets, one faces new challenges, which directly impact upon the commercial viability of ODSs. These can be roughly grouped in three categories.

1. Identification, specification and design of *architectural components* to support these new features. Examples are concepts and entities within emerging management frameworks [39], as well as commercial contract support architectures, which should support users in expressing their business policies and requirements and thus, facilitate business transactions.
2. Provision of mechanisms which would accelerate users' confidence in accepting new characteristics of services in an open information market and thus *alleviate uncertainty* about the whole spectrum of issues to which the telecommunication and computing societies have not been previously exposed. This uncertainty arises from:
   a) the lack of users' previous experience with new services that are proliferating and evolving at a dramatic pace and thus uncertainty about what benefits can be gained from these,
   b) the problem of succinctly expressing the semantics of services required,
   c) the problem of discovery of services in the global market place.

   Some of these concerns (such as *a*) go beyond the scope of technology and also represent a new field of inquiry for other disciplines, e.g. psychology, consumer behaviour, economics and logic. Others (e.g. concerns *b* and *c*) represent new research topics for computer science.
3. Solving a variety of new *resource problems* in ODSs which arise from inherent uncertainty of an ODS environment, but also from the characteristics of consumers and

providers. For example, different parties, in striving to achieve their own and often mutually conflicting objectives can take advantage of private information, behave opportunistically or take advantage of the actions of others. As a manifestation of these actions, an increased uncertainty of service delivery, i.e. QoS[2] delivery can arise. This particularly refers to those information services which at a given point in time can be regarded as non-standard and which can involve significant technical complexity. Further, this uncertainty can in turn cause an uneven spread of the benefits of the underlying resources among interacting parties (as discussed in section 2). The latter is a direct consequence of the twofold nature of QoS in an ODS. It has economic aspects since it is (next to quantity and price) the major element of competitiveness and an important element of contracts, as well as technological aspects since it describes requirements regarding physical resources in an ODS. In order to alleviate the ‘unevenness’, these potential behavioural patterns need to be taken into account when designing mechanisms for efficient allocation of resources among parties.

It is this last category of the problems that is the subject of this paper: i.e. a new dimension to the problem of efficient resource allocation in an ODS, as a result of the simultaneous existence of different parties and a number of new sources of uncertainty inherent to ODSs. This includes issues that have not been extensively studied in computing and communication communities to date (and are indeed a major area of inquiry in modern economics). We take a step in this direction in that we undertake a study of a mechanism, which can maximise players’ (i.e. users’ and service providers’) utilities[3] under the above conditions. This mechanism involves design of optimal service *contracts* between a user and a service provider in an ODS.

Since these problems have a lot in common with economics which indeed can be regarded as a science of cooperation with respect to the utilisation of resources [40], we

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[2] Since our view (the reasons for which are given in section 4) is that uncertainty of service delivery is mainly related to its quality, we will use the terms service delivery and Quality of Service delivery interchangeably hereafter.

[3] Utility is the level of satisfaction that a person gets from consuming a good or undertaking an activity. In economics it is used to summarise the preference ranking of customers.

will adopt the economists' style of thinking to address them[4]. We will argue that the relevant results of Game Theory (GT) can provide solutions for a range of emerging resource issues in ODSs. For instance, the above mentioned problems are a result of the *information asymmetry*, i.e. a situation in which at least one of the players possess private information which gives an informational advantage. This can be modelled by using a non-cooperative game with asymmetric information structure. A representative of such a game is the principal-agent model, which is an important component of economic Agency Theory (AT)[5].

In the next section we outline new sources of uncertainty regarding services in ODSs and discuss the impact of uncertainty on the resource allocation in an ODS. In section 3, an overview of current contributions of GT in telecommunications networks and distributed systems is given, followed by a view of its extended role in emerging ODSs in terms of Agency Theory applications. Section 4 focuses on how one should go about describing agency relationships associated with the delivery of QoS in ODSs, what we call a *QoS game*. Different solutions for this game are also given, followed by a demonstration of the application of AT with the trading service, currently under proposal and development in several standardisation bodies and research/commercial initiatives. The conclusion and future research are given in section 5.

2 Uncertainty of services in open distributed systems

Uncertainty which is associated with services in present information systems emanates mostly from different technical variables such as reliability, availability and responsiveness. However, ODSs bring additional factors of uncertainty, arising because:

- interactions and transactions occur in a more uncertain environment, not only in technical but also *economic* terms (e.g. competition),

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[4] Our economic-driven approach has similarity to several other research efforts (as discussed in section 3), in particular with the approach taken in [7], whereby the price mechanism was designed to provide incentives for users to use only as much of network (the Internet) resources as they required.

[5] Results of cooperative GT can also be utilised, e.g. enterprises forming coalitions to exploit economies of scale, scope and probably more importantly, *information*.

- the interactions between users and providers center around new variables, such as *QoS*, which are harder to specify, measure and monitor, and which involve some level of subjectiveness,
- services can involve significant level of technical complexity, which can affect users' ability to acquire perfect knowledge (information) about them.

We now take a closer look at different sources of uncertainty in an ODS, and how these can impact certain classes of ODS services.

2.1 Sources of uncertainty in open distributed systems

Sources of uncertainty in an ODS can have their origins in subjective and objective factors, as depicted in Fig. 1. While some subjective factors have been mentioned in section 1 (i.e. the categories 2 and 3), objective factors include the following.

1. The unpredictable and dynamic competition variables of an environment which include:
    a) the number of users and service providers who interact by using underlying resources (this for instance can determine the price of using these resources); this is also an indicator of the acceptance level of technologies, e.g. as evident in dramatic increase in the number of Internet users, but also in less than expected adoption level of EDI technology,
    b) changes in users' QoS expectations and service providers' QoS offerings, which bring a new competitive perspective, i.e. QoS competitiveness, as for example evident in many new telecommunication services, such as Intelligent Network services (e.g. automatic call distribution feature) and personal communication services,
    c) new service types as a result of new technological opportunities, which can increase the demand for existing resources, e.g. Mosaic facility [20], which has contributed to the dramatic increase of the Internet traffic (which has led to a need for more bandwidth).

2. Interactions across large geographical distances (even globally), which bring about unobservability of other parties' behaviour. This, coupled with subjective factors (conflicting goals and opportunistic behaviour), is a prerequisite for *agency problems* (as elaborated in section 4).
3. Crossing administrative boundaries, since it is harder to get full insight into the status of relevant parameters in external domains, e.g. competence of potential service providers.
4. New technology issues associated with services. These include:
   a) the user's search for, and selection of appropriate service provider(s),
   b) negotiations with providers about service contract terms (e.g. QoS),
   c) service delivery, which includes new technology requirements, e.g. end-to-end QoS, multimedia QoS (e.g. stream synchronisation), broadband and mobile QoS requirements.

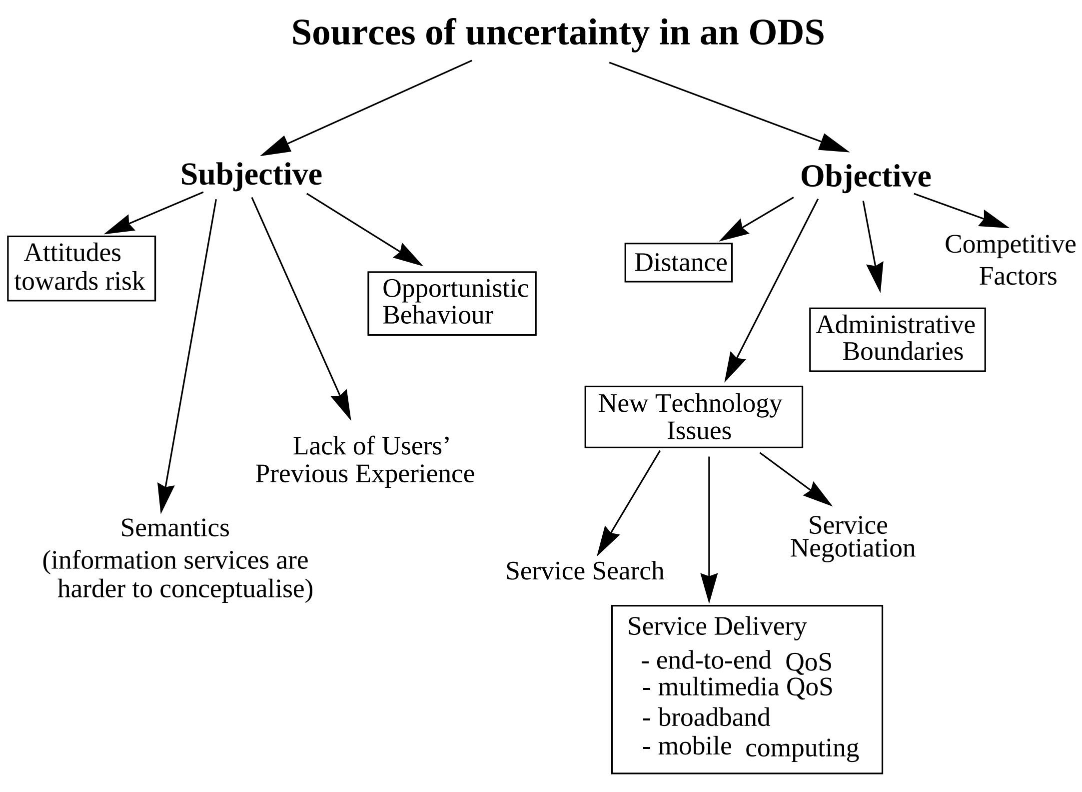

Figure 1 Sources of uncertainty in open distributed systems

In this paper we are specifically interested in the uncertainty accompanying service delivery in an ODS[6]. This uncertainty arises from the objective factors, e.g. distance, new technologies, crossing of administrative boundaries but also due to subjective factors, e.g. opportunistic behaviour (these factors are captured within the boxes set out in Fig. 1). It is worthwhile to note that these factors can also be separated into the two groups: the uncertainty of the *environment* and uncertainty arising from the *asymmetric information*.

2.2 Types of ODS services particularly affected by uncertainty

From the pace of new services appearing on the markets, it is not hard to predict that there will be a large number of different service types in an ODS. However, some of the services will be affected more and some less by the factors of uncertainty identified above. By adopting the reasoning based on the transaction cost economics approach [43], in a similar manner as developed in [24], one can identify those services for which uncertainty can be a serious problem and to which AT can be applied. Typically, such services will have the following characteristics.

- Several service attributes (characteristics) of relevance for users. This implies complexity in terms of service description, i.e. the amount of information needed to specify the service attributes which in turn imposes more information requirements on the side of users. Further, it is hard to expect that users can have the same level of information as the service providers who may have developed the service. These are some prerequisites for information asymmetry. Any value-added information service can be a good example, e.g. business insurance policies [24] and a tourist information service [29]. On the contrary, in the case of simple services, such as electronic stock exchanges and electronic trade of commodities, users can obtain perfect information about services and agency problems do not exist.

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[6] This assumes that ‘pre-service’ operations, such as service search and service negotiations have been successfully completed at a previous point in time.

- Non-standard form (i.e. idiosyncratic or asset-specific in terms of transaction cost economics). This means that the service is customised for a certain class of customers or for a certain class of application, and that it cannot be readily used by other firms, or in other applications. In the absence of market pressures, providers of such services can engage in opportunistic behaviour, as also discussed in [41].
- Suitable to be exploited by the service providers for gaining a competitive advantage. Any value-added information service, especially one that can play a strategic role for the competitiveness of the service provider can be a possible candidate. Several examples from the eighties confirm this, e.g. early computerised reservation systems (e.g. American Airlines SABRE system) as well as electronic ordering systems (e.g. American Hospital Supply's ASAP system), which have brought significant profits to their providers. A more recent example of a similar service comes from the insurance sector, whereby an electronic integration service is provided by insurance careers to independent agencies [45]. Another example is an electronic transportation chain management system, increasingly used in port communities [44]. It is interesting how in such a system an opportunistic behaviour can arise, according to the scenario developed in [41]. The authors analyse the trust of a shipping company regarding the performance of a transportation chain management system run by a company in which all shares are owned by a large transportation company. The uncertainty about route evaluation can arise from the fact that the transportation management system can suggest an 'optimal' route to be the one where the transportation company operates, although there are cheaper routes (and that knowledge is not readily available to the shipping company).

It is important to note however, that the above scenarios are typical of the so called 'biased markets', and that regulatory pressures can contribute to change towards 'unbiassed markets' [24], in which the problem of asymmetric information is alleviated. In other words, while at a certain point in time the uncertainty of a particular service can be a problem, regulatory and market pressure can influence a shift towards a more 'perfect' market structure. For example, as an initially non-standard service gains wide acceptance, a requirement for a standardisation of the service can arise at a later point in time.

The presence of uncertainty arising from information asymmetry has an impact on the way the benefits of services are spread across parties involved. It is a well known fact in economics that information asymmetry alters the ability of a perfect market to allocate resources efficiently [33]. This fact can be applied to analyse an the impact of uncertainty on resource allocation in ODSs, as is done in the following.

2.3 Impact of uncertainty on resource allocation in open distributed systems

From previous discussions, one can conclude that as ODSs develop they will increasingly resemble complex economic systems in which interactions between parties take on new forms and bring novel requirements. For certain classes of services in which uncertainty can be a serious problem, as identified above, the adoption of contracts can reduce such an uncertainty, in a manner similar to the real world scenarios.

The relationship between contract specification (which is at the heart of most business transactions) and underlying resource requirements in an ODS is illustrated in Fig. 2. The business contract specification requires an understanding of contracts from the economic and legal points of view, as well as typical business practices related to contracting. This includes the identification of important contractual terms, as well as different types of contracts applicable to different situations. The contractual terms specify the *business* level interaction in an ODS environment. A typical commercial contract involves several contractual terms (e.g. payment terms, contract length, obligations and liability of parties etc.). An important term which unifies both user driven and technology concerns is *quality*. It embodies (normally a small number of) broad areas of users' concerns about a service. We refer to these service specific QoS issues as *QoS aspects*. They belong to the domain of *service* level interactions between agents. These in turn need to be mapped to *technology*-related QoS issues, which we refer to as QoS characteristics[7]. This mapping can be expressed by a QoS matrix (Fig. 2), the cells of which contain relevant performance parameters, which can be objectively or subjectively measured variables [29].

Therefore, contract specification takes into account underlying resource requirements via QoS specification. Consequently, the level of uncertainty of the provision of QoS, as it is recognised in the contract, has a direct impact on different resource issues, e.g. the way resources are allocated, shared and charged. This uncertainty arises from the fact that QoS monitoring and enforcing is harder to effect and often can involve (unjustifiable) costs. We note here that other contract terms can be monitored with more certainty (as elaborated in section 4).

In general, enterprise type interactions between players in ODSs are related to the QoS management in ODSs. This in turn encompasses specification, mapping (between layers), negotiation, resource allocation, admission control, performance maintenance &

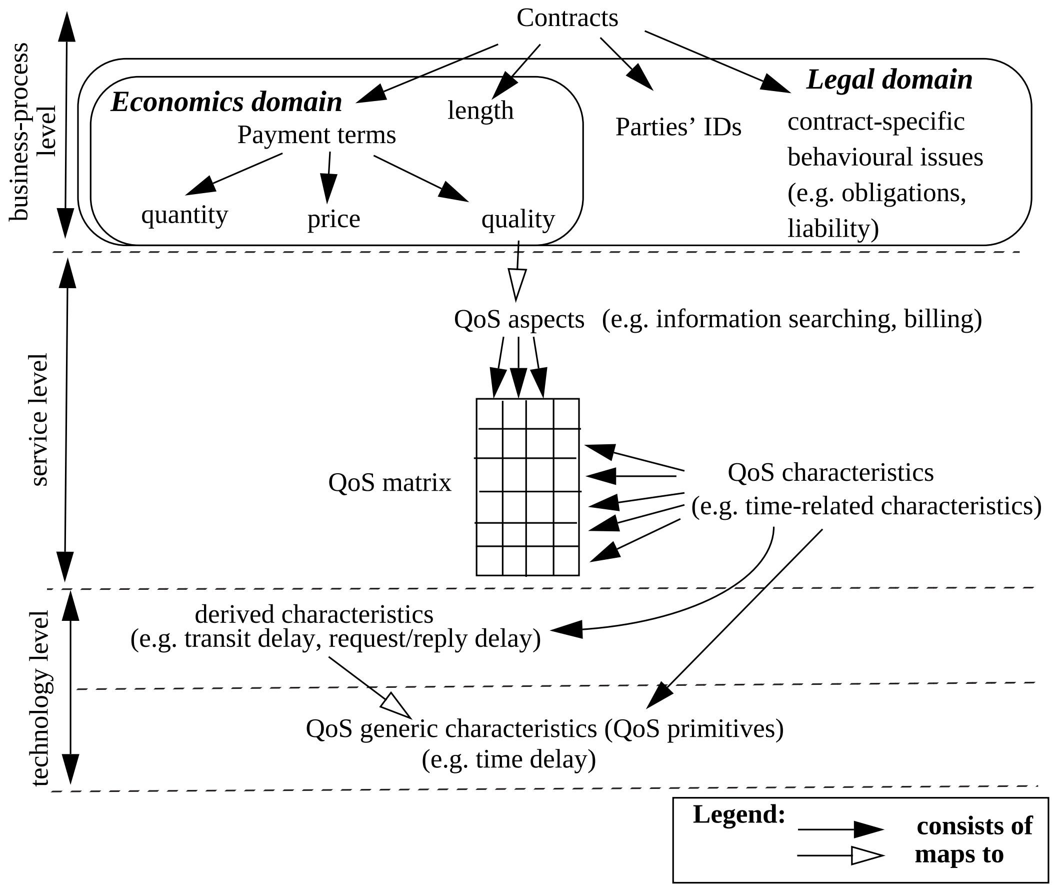

Figure 2 Relationship between contract specification and QoS issues

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7. It is useful to distinguish between the generic QoS characteristics (e.g. time delay) and derived QoS characteristics, which are derived from the generic characteristics to be applied to a specific/concrete scenario, such as transit time [18].

monitoring, policing and renegotiation paradigms, as developed in [16]. The focus of this paper is on the mapping of enterprise interactions (embodied in the contract) onto a resource allocation subset of ODS QoS management in order to provide efficient implementation of services in ODSs. These specific QoS management functions reflect user enterprise objectives and policies which need to be realised in an unpredictable and non-deterministic ODS environment, as indicated previously.

We highlight the fact that new resource problems in ODSs emerge not only as a result of novel technical factors, but also as a result of a number of human-driven, non-technical factors embodied in users' enterprise policies (these are for instance, within the domain of the ODP and TINA enterprise viewpoint[8]). For the commercial success of an ODS architecture, one needs to design resource mechanisms which would take into account the undesired properties associated with interactions between different users of ODSs.

We view topics from information economics such as *optimal incentives* design and a more general optimal *contract* and *mechanism* design[9] [22], (in which the importance of uncertainty on resource allocation is taken into account) as a promising methodology for the design of such mechanisms in the context of ODSs. As the first step in this direction, we will use a specific theory from information economics, i.e. Agency Theory (AT) to model and solve information asymmetry problems between a user and a service provider in an ODS. An appealing AT property is that it can incorporate both, the human and technological factors described above and unify them (via QoS issues) in the description of the interactions of players while playing what we call a QoS game. Since AT can be seen as a specific paradigm within the broader topics of Game Theory, we first illustrate some GT applications in solving different resource problems in telecommunication networks and distributed systems, followed by a view on its extended role in ODSs. The objective of this to highlight the novelty of applying GT in the context of ODSs.

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8. RM-ODP (and TINA) master the complexity of ODSs by separating concerns of different parties involved, in enterprise, information, computation, engineering and technology viewpoints [17].

9. Mechanism design is a broad topic which addresses situations in which there may be multiple agents [22].

3 Game Theory - application to open distributed systems

Game theory is a formal analysis of conflict and cooperation among rational decision makers (e.g. human individuals, corporations, nations), pursuing their own objectives. As a modelling approach, it has been used in the social sciences, especially economics, but also, in recent decades in modelling different problems in telecommunication networks and distributed systems areas.

3.1 Applications of GT to telecommunication networks and distributed systems

GT has proven to be beneficial in offering solutions to a number of technical problems which arise in telecommunication networks and distributed systems, owing to its value as a rigorous mathematical paradigm with predictive power. We illustrate some applications below[10].

3.1.1 Telecommunication networks

GT concepts have been applied to formulate different resource problems in telecommunication networks. Examples are the routing problem in a telephone network [13], [26], flow control in computer networks [14], [37], flow control in multiclass [28] and general networks [14], routing in multiservice networks [9], call admission [27] and congestion control [38] in broadband networks. In addition, GT has been applied to model and solve some higher level issues (e.g. pricing) associated with telecommunication networks. For example, [11] investigates stable coalitions between different national carriers when cooperating in the international network to gain benefits from time zones effects. In [7], the role of pricing policies in multiservice networks is studied; it was found that it is possible to set the prices so that users of every application type are more satisfied with the combined cost and performance of a network with service-class sensitive pricing.

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[10] Due to space limitations (and probably with injustice to many authors), it is not possible to provide a comprehensive survey of all applications of GT to networks here - rather some typical examples will be mentioned.

3.1.2 Distributed systems

Applications of GT to distributed systems issues are not as numerous. While some technical problems in this area (e.g. processor scheduling [25], load balancing [10], [42], file allocation [10], resource management for concurrent computations [42]) have been solved by applying principles from microeconomics (e.g. price mechanism, auctions etc.), GT has been used to provide a supporting theoretical framework (e.g. to prove Pareto optimality of particular resource allocation schemes [10]). In addition, some references to GT can be found in [15], which investigates oscillatory and even chaotic dynamics of distributed computation in which agents have incomplete knowledge and imperfect information on the state of the system.The paper investigates the analogy between distributed computation and biological ecosystems/human economies and in relation to GT, argues that, in distributed computing, the rationality assumption of GT can be explicitly imposed on their agents, thereby making these systems amenable to game dynamic analyses, suitably adjusted for their intrinsic characteristics.

3.2 Application of game theory to ODSs: agency theory approach

While the potential of GT for applicability to networks and distributed systems is increasingly being recognised, it is interesting that not much work has been directed towards incentive compatibility[11] problems (with the exception of the work reported in [7], [37] and [38]). Rather, the focus has been on designing mechanisms which achieve some *technical* optimality criteria, mainly at the network/transport layers. Also, most of the research so far has assumed perfect information, e.g. agents are jobs and processors [10]. This was a reasonable assumption for the types of problems dealt with, but unrealistic in the context of ODSs, as will be explained.

New characteristics of ODSs contribute towards a number of higher level problems, as already highlighted. We argue that application of GT in the context of an ODS can be extended towards modelling roles, actions and interactions among players in such an en-

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[11] The concept from economics which characterises those mechanisms for which participants in the process would not find it advantageous to violate the rules of the process (with ultimate goal, such as Pareto-efficient allocation of resources [23]).

vironment (in a similar way as it is used in GT economic models). GT appears to be the natural candidate to address these novel issues as it can integrate both human and technological issues (via QoS), when modelling interactions between ODS actors. To select and formulate the appropriate GT model[12], the *information structure* of the game should first be identified. One of the most important and interesting kinds of information is *asymmetric information* and the different types of agency relationships which arise as a result. From arguments given previously, it is evident that a large class of information services in an ODSs can be characterised by asymmetric information among service users and service providers, and hence can be studied in forms of agency relationships (particularly with respect to QoS provision; in the following we refer to these problems as QoS games).

Agency theory (AT) in general terms focuses on a multitude of problems which characterise relationships (i.e. games) between one or more players called *principals* and one or more other players called *agents*, who make decisions and/or act on behalf of principals. These problems acquire interest if there is some *uncertainty* emanating from information asymmetry and environmental risk (referred to as *agency problems*). AT aims to find *optimal contract designs* between principal(s) and agent(s) under the above circumstances. It is now widely recognised that agency problems dominate many economic activities within organisations and across markets, and we would argue that these would also characterise interactions between players utilising ODSs.

There are two broad categories of information asymmetry which are of interest for AT. The first one refers to situations which occur *after* the contract between an agent and a principal is set up (ex-post), whereby the agent, in order to pursue his own objectives, can *act* in a way which is not optimal for the principal (but the principal cannot observe it). This type of situation is called *hidden action* (or moral hazard). Another type of problem is called *hidden information* (or adverse selection); it arises when an agent has knowledge not shared with the principal, and bases his decisions on that knowledge. Hence, it refers to circumstances *before* the contract is signed (ex-ante). The terms moral hazard

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[12] Basic concepts from game theory used in this paper are given in the Appendix

and adverse selection come from the insurance industry.

The solution to a moral hazard problem is the use of an *incentives* mechanism, i.e. devising a contract so that the agent will in his own interest take actions that the principal would prefer. The solution to adverse selection is so called (market) *signalling*, where the party in possession of superior knowledge signals what he knows through his actions [22]. We now turn to description of agency problems in an ODS setting, and illustrate an AT application with a trading service.

4 QoS delivery in ODSs: agency problems and solution

An important characteristic of open information markets, enabled by ODSs is the availability of information services offered at different levels of quality for different prices, providing a greater choice to users. The first step which a user (or service requester, SR) in an ODS would normally perform is to locate an appropriate service provider (SP)[13], based on the required service type and service attributes, e.g. quality, quantity and price. This can be done by using an information broker component within an ODS, such as the ODP trader [19] (as will be explained in section 5). The combination of these attributes, i.e. <*quantity, QoS, price*> will constitute a central part of a service contract which binds the SR and the SP. Note that if a service can be regarded as a homogenous commodity (i.e. with a single QoS level), the standard microeconomic supply/demand theory can be applied in order to find an equilibrium (achieved through the price mechanism). However, QoS adds an additional complexity to the problem of finding an equilibrium, as will be described in the following.

4.1 User-service provider relationship: motivation for agency theory modelling

Assuming that SRs and SPs are rational decision makers and given a fixed amount of service quantity, the SR will be interested in maximizing her *perceived QoS/price ratio*, and similarly, the SP in maximizing his *offered QoS/cost ratio*. In other words, the SP tries

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[13] Optimal search is another important topic from information economics [22], which is not addressed in this paper.

to maximize his net wealth, which is the difference between the payment received from the SR and costs in providing the service, while the SR tries to maximize her net wealth, i.e. the difference between the monetary value she obtains from the service and the price she pays for it. If *perfect* (or more specifically *symmetric)* information is available to both players[14], an efficient agreement between the SP and the SR can be determined for this simple QoS game. Such agreement is often termed *first-best design of cooperation* [40], and can be arrived at when two players have different QoS/price options (and both know these) and successfully complete the QoS negotiation process. The agreement commits the SP to a certain performance in exchange for a certain pay to be made by the SR.

However, the assumption of perfect information is unrealistic in ODSs, as shown in section 2. It is likely that one or more sources of uncertainty become non-negligible in the process of service provision, directly impacting players' benefits in such systems. We will assume that changes in agreed upon quantity and price of a service can be detected (in fact, price of a service can change dynamically, but there are different mechanisms to inform SRs about this, e.g. service contract can contain a clause about this, SRs can inquire about the price through say a trading service). However, a SP's performance regarding QoS term of contract is harder to monitor due to the unobservability of the SP's actions. Hence, given perfect information about price, we see a major source of uncertainty in terms of the *QoS* delivered to the SR as a result of the performance of the SP. One therefore needs to consider this uncertainty when designing contracts between players. This is indeed a non-trivial resource allocation problem since it involves:

- QoS mapping between a user's QoS view and the corresponding technology variables. This is hard problem in itself, since it involves QoS specification and measurement. To cope with the proliferation of new services and user driven requirements, one needs to develop a generic, service-independent and user-driven methodology for QoS specification and measurement. Such a methodology (e.g. [3],

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[14] The Game Theory terms which are used extensively in this section are summarised in Appendix.

[29]) is a prerequisite for a user to be able to measure QoS as the *output* of the SP efforts (due to the information asymmetry the SP's effort itself is not measurable).

- Incorporating dynamic effects of the system caused by other users utilising ODS resources. This forms a part of the ODS environment uncertainty. Such effects can be taken into account in a contract design via appropriate distribution function that models this state of Nature.
- Designing an appropriate reward structures which will provide incentive mechanisms for the SP performance and optimal spread of risks among the SP and the SR based on their characteristic in terms of their *attitude towards risk*. For example, a *risk aver*se decision maker prefers a certain choice to a risky choice with the same expected utility. A *risk neutral* person is indifferent to these alternatives. A *risk lover* is the opposite to a risk averse individual.

It is important to note that these resource problems are particular relevance for the specific type of information services, as identified in section 2. Since for such services a common denominator of the relationships between users and service providers is agency relationship, we study how AT can be applied to these cases.

Further, in the presence of uncertainty, the first-best design of cooperation is generally not achievable, and one seeks the so called *second best agreement* (see 4.2.4). Following in the spirit of AT, this difference is called *agency cost* and it is borne by the principal, agent or both, depending on their attitudes towards risk. Broadly speaking, agency costs are incurred from discrepancies between the objectives of the principal and those of the agent [12]. We look more closely at these issues in the context of service delivery in ODSs. Using the AT terminology, the SR has the role of a principal and the SP has the role of an agent [30].

4.2 Service provider/service requester QoS game: basic model

Firstly, we outline a general *framework* for analysing a game, i.e. a set of recommendations about the GT modelling procedure. The following steps can be used to describe a game:

- Identify the *rules of the game*, i.e. *players*, their *actions* and *outcomes.* To this end, one needs to consider where the rules come from for a particular scenario, i.e. to determine the operational settings in which a game is played (e.g an organisation or market).
- Look at the *information structure* of the game and define its type (e.g. a game with perfect, certain, asymmetric or imperfect information). If the game is of asymmetric information, then the models developed within AT literature can be utilised, as will be described below.
- Succinctly define a *formal model* of the game. This includes the order of actions and events, forms of players' utility functions, constraints, and Nature's probability distribution.
- Find an *equilibrium* of the game, e.g. a solution which gives an optimal allocation of resources.

We will follow these recommendations in analysing a SR/SP QoS game in the context of ODSs.

4.2.1 Rules of the game

We assume that the SR has already selected an appropriate SP from possible candidates, so that the influence of other SPs is implicitly incorporated. Namely, competition for agents (and principals) directly influences selection but not QoS delivery. The dynamics of competitive forces, can be studied under a more general model which includes multiple agents and/or principals and this is a subject of further study. Under this assumption there are two players in this QoS game, the SR and the SP. The SR wants to hire the SP, because her wealth (e.g. in terms of her business opportunity) depends on the services which the SP can provide. The SP can offer services in various quantities and qualities. To simplify the model, we assume the case of one unit of service which can be delivered at various levels of quality. Each QoS level involves a particular effort, or disutility to the SP.

Formally, the SR's action is to offer a contract with a pre-defined payment scheme p (finding such a payment is the central problem of the principal-agent model, as will be described in the following). The SP's action is manifested by his decision to accept or reject the offer. The SP will accept the offer if it can yield him a utility which is greater than his, *reservation utility m*, the minimum that induces him to work. If the SP accepts the offer then he needs to choose an action x, from the set of feasible actions X, $x \in X$. This action results in a particular level of outcome $y = y(x)$, but also incurs disutility $c(x)$ to the SP.

The order of actions depends on the market power of the players. For example, if many principals compete for one agent this can be modelled by letting the agent move first. In the context of an ODS, this will be the case when there is a small number of particular types of information service providers, in which case their opportunistic behaviour can result.

It is normally assumed that function y represents the monetary value and it is increasing in x. The SP's utility function U_{SP} is decreasing in effort x and increasing in payment p. The SR's utility function U_{SR} is increasing in the difference between output and payment.

4.2.2 Information structure of the game

As discussed earlier, for a particular class of ODS services this QoS game can have an *asymmetric* information structure. There are two types of private information which the SP can possess and which the SR may not be able to observe (but would normally be aware of). The first refers to the unobservability of SP's *effort* in delivering agreed levels of QoS (moral hazard problem). The other type refers to SP's ex-ante knowledge about some variables relevant for QoS which the SR does not know (adverse selection). Hence, there is the possibility of a hidden action or hidden information type of situation, exploited by the SP with respect to service delivery. To illustrate the applicability of AT in modelling the QoS game, we formulate a simple model for the hidden action type of this QoS game.

It is important to first note that agency relationship involves two types of problems. One problem arises from goal divergence, opportunistic behaviour and unobservability of players' actions. The second problem is one of risk sharing, i.e. which arises when uncertainty of the players' environment (i.e. exogenous uncertainty) can occur. The former problem will be first discussed in the context of an ODS environment characterised by certain information, via use of an example of a tourist information service [29]. This will be followed by a more general problem which includes exogenous uncertainty of an ODS environment (in 4.2.3).

Let us assume that a tourist information service provides residential and business users with access to a multimedia tourist information directory with a range of tourist information, e.g. airline carriers, accommodation, packaged tour deals. Let users be capable of performing the following operations: search through directory information, viewing particular information found after the search on their multimedia workstations (e.g. a video presentation of a particular resort, hotel rooms, potential entertainment guide, accompanied by high-quality audio information), booking (e.g. specific accommodation, flight), select preferred mode of billing, and customisation of the service according to their own needs. Each of these operations represent a TIS service aspect, which depends on one or more technical variables, e.g. response time, reliability, bandwidth, jitter etc. Further, the TIS SP can specify a wide range of TIS QoS levels, which are function of each of these aspects.

However, due to the complexity of this service it is hard for a user to monitor the exact performance of the TIS SP. For example, the TIS SP can agree to search all the primary tourist providers in a given region, but due to the vested interests in some of these providers, the TIS SP can contact only this subset of potential providers. Although, a user can request some kind of search logs, this can involve additional costs (and still these logs need be trusted). An alternative solution can be in providing an incentive mechanism to the TIS SP. For example, rather than paying on the basis on the number of search domains, a user can pay on the basis on how comprehensive a search report is. Similarly, a primary tourist provider can pay a commission to the TIS SP for each sold service of that primary provider.

Hence, an incentive mechanism of some kind is sought which will induce the TIS SP to perform according to the best interest of its customers (both end-users and primary tourist providers). One payment scheme which provides incentives to the TIS SP can be a linear scheme[15] of the form $p(y) = f + sy$, where *f* represents a fixed fee, and *s* $(0 \leq s \leq 1)$ denotes a *share* of output y. If s = 0, the SR pays a fixed fee to the TIS SP, and with s = 1, the TIS SP has an incentive to do his very best. Since we assumed that there was no uncertainty of the underlying ODS environment, the players' attitudes towards risks associated with this uncertainty do not come into perspective. However, in the presence of the exogenous risk of an ODS environment, this changes. Now, the players' attitudes towards risk determine the optimal share *s* of such risks. This is a typical principal-agent problem, i.e. finding an optimal payment scheme which provides incentives and also different risk sharing between players. For example, due to the unpredictable load of the system between an end-user and the TIS SP, the end-user cannot deduce whether say the low response time of the TIS search aspect is because of the congestion of the system between them, or because of some TIS SP specific cause.

In the following, we will show how such a payment scheme can be derived for a more general case, i.e. when there is an environmental uncertainty.

4.2.3 Model of the game: hidden action type

As just indicated, due to the influence of environmental uncertainty of an underlying ODS, the SR cannot observe how well the SP is performing. This state of nature is exogenous to both the SR and the SP (and they are aware of this), and can be modelled as a random variable $\tilde{\theta}$. This uncertainty can result from either numerous technical factors, or due to unpredictable, increased demand from other users, which results in performance/

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[15] There can be a number of other incentive payment schemes, e.g. *threshold* contract, which provides incentives in terms of reaching certain target levels of effort.

QoS deterioration for the (SR,SP) pair under consideration. The SR's gross wealth (outcome) $\tilde{y}$ is then a function of the SP's action x, but also the exogenous risk $\tilde{\theta}$,

$$\tilde{y} = F(x,\tilde{\theta}) \tag{1}$$

Since the outcome y is affected (but not completely determined) by the SP's actions [2], [30], a fee for service can no longer be agreed upon by simple negotiation (as in the first-best design of cooperation). As before, to cater for the SP's possible hidden action, the SR is willing to provide incentives for the SP's actions via an appropriate reward that is included in a pay function (which will be paid to the SP after the realization of the output y),

$$p = p(y) \tag{2}$$

We assume that the outcome y is expressed in terms of monetary income (wealth) which is a transferable and measurable quantity [2]. The net SR's wealth will then be $y - p(y)$. On the other hand, the SP's net wealth (also after the realization of the output y) is $p(y) - c(x)$, where $c(x)$ represents the SP's disutility (again in terms of money equivalent). Note that these are the net wealth, *after* Nature has played out. If we include an environmental uncertainty *before* the realisation of the SP's action, the randomness is incorporated by substituting equation (1) for y. Thus the following values describe net wealth (i.e. pay-offs in GT terms) of the SP and the SR:

$$\tilde{w}_{SP}(x,p) = p(F(x,\tilde{\theta})) - c(x) \tag{3}$$

and

$$\tilde{w}_{SR}(x,p) = \tilde{y} - p(\tilde{y}) = F(x,\tilde{\theta}) - p(F(x,\tilde{\theta})). \tag{4}$$

Being rational decision makers, the SR and the SP aim to maximize their welfare, derived from their wealth, given by (3) and (4). The welfare can be formalised as the expected values of their utility functions. If $U_{SR}(\tilde{w}_{SR})$ and $U_{SP}(\tilde{w}_{SP})$ represent the SR's and the SP's utility functions respectively, their objectives are to *maximize* expected values, i.e. $E[U_{SR}(\tilde{w}_{SR})]$ and $E[U_{SP}(\tilde{w}_{SP})]$, or their certainty equivalents [40], i.e. $u_{SR}^{-1}(E[U_{SR}(\tilde{w}_{SR})])$ and $u_{SP}^{-1}(E[U_{SP}(\tilde{w}_{SP})])$, where u_{SR}^{-1} and u_{SP}^{-1} represent von

Neumann-Morgenstern utility functions [22].

Now, the SR chooses a *payment scheme* $p \in P$, which prescribes incentive for the SP, and 'invites' the SP to accept it. The SP decides whether to accept the SR's offer or not, taking into account his *reservation utility*, represented by a reservation constraint, *m*. Thus, the SP accepts a payment *p*, only if the welfare obtained is not below this constraint level [40], i.e.:

$$E[U_{SP}(\tilde{w}_{SP})] \geq m \tag{5}$$

If the SP decides to accept a reward scheme *p*, he will choose such an action *x* which will maximize his expected value $E[U_{SP}(\tilde{w}_{SP})]$. It is assumed that the SR knows this and will take the SP's decision into account by regarding it as a constraint; given this fact, she will then try to maximise her expected value $E[U_{SR}(\tilde{w}_{SR})]$, i.e. to determine exact values for the coefficients of the optimal payment scheme, given by (2). After the realization of the outcome *y* is known, the actual payment *p(y)* will be provided to the SP.

4.2.4 Solution concepts

In order to find an *equilibrium* of the game, i.e. to design a *contract* which will be *optimal* for both SP and SR, there are two alternatives. One is more GT oriented, i.e. searches for Nash strategies, which involves a guess that some combination of strategies is an equilibrium, and then testing them [34]. Another analytical approach, which will be used here, is to set up a maximisation problem (set up payoff functions with constraints) and solve it using the first order conditions. This approach can be applied to this game since it is a sequential game, in which the last player's maximisation problem can be embedded in the first player's problem as a constraint [34][16]. Hence, the maximisation problem consists of maximising $E[U_{SR}(\tilde{w}_{SR})]$, subject to the maximal value of $E[U_{SP}(\tilde{w}_{SP})]$ and reservation constraint (5). It is important to emphasize here that the hidden action problem cannot be solved in its general form [40]. Rather, for the equilibrium to be fully described, one needs to assume specific forms of a payment scheme, util-

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[16] This however presumes knowledge of the others' risk aversion factors etc. Since this may not be a realistic assumption in the context of ODSs, an alternative method can obtain this on-line (see 4.4).

ity functions of players, Nature’s distribution function and the dependence of outcome on risk associated with the environment (environmental uncertainty).

Due to the size of the space of all possible forms of fee functions, it is a common practice in AT literature to assume a simple functional form. The adoption of appropriate simple forms which provide models that are closely related to business interactions in the real world makes the problem solving more practical. This might be justified by the fact that complicated contracts incur transaction and computation costs (e.g. costs of writing and enforcing contracts) [12]. One such frequently used functional form which quite realistically models typical business situations, provides incentives and also different risk sharing balancing is a *linear contract* form [34]:

$$p(y) = f + sy \tag{6}$$

where, f is a *fixed* amount, that the SR pays to the SP, and s $(0 \le s \le 1)$ denotes a *share* of output y; if s = 0, the SR pays a fixed fee to the SP (and thus bears all the risk), and if s = 1, the SP bears all the risk. For any other value of s, the risk is borne by both players; the balance of which depends on players’ attitudes towards risk; the latter in turn determines the form of his/her utility functions. Formally, a risk averse individual has utility function with a diminishing marginal utility, and the utility curve has a positive slope and is concave (e.g. an *exponential* function). A risk neutral person has a *linear* utility function. A risk lover has a convex utility function. The level of risk aversion can be expressed with the coefficient: $\alpha = -u''/u'$, where u represents an individual’s utility function, and u' and u'' are first and second derivatives respectively. In the standard principal-agent scenario, it is assumed that a principal is risk-neutral (as she can diversify), and an agent is risk-averse (he cannot diversify) [33].

Finally, some comments on the distribution function which models Nature’s behaviour need to be made. The form of this function depends on which random variable this function models. In the context of ODSs, this may include an engineering parameter, e.g. reliability, delay etc. But, it is also possible to include other variables such as the unpredictability of other customers’ utilisation of the same resources which the SR and the SP need to access (e.g network, trader etc.).

Now, if specific forms for the functions y , $\tilde{\theta}$, *c (x)*, $U_{SR}(w_{SR})$ and $U_{SP}(w_{SP})$ are known, then equations (1)-(6) can be used to determine analytically the coefficients *f* and *s* for *p(y)* and the agent's action *x* for an optimum trade-off between *risks* and *incentives.* These variables describe the game's equilibrium, i.e. an optimal contract between the SR and SP (in terms of AT, the second best agreement). Specific forms of these functions will be assumed for the example that follows, i.e. the trading service; the form of the optimal solution will also be given and discussed.

4.3 Example: a trading service

One of the central services in an ODS which supports establishment of the market of information services is a trading service. We will focus on the functionality of this service according to the ODP specification [17], [19].

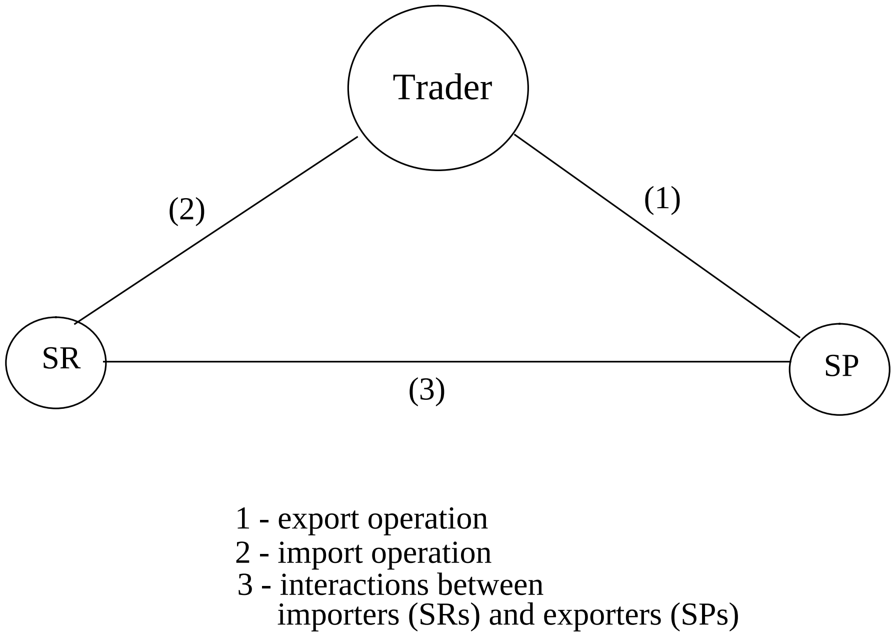

Figure 3 Interactions between the Trader and its users

The trading service is implemented by the ODP component called Trader (similar concepts/components are also present in architecture such as ANSAware and TINA and is likely to be adopted within the OMG standards). This component stores service offers exported by SPs, and provides a search capability to SRs, so that advertised SPs' offers which match SRs' requests can be found and then imported, Fig. 3 (thus, the trader function is similar to one of yellow pages). Optionally, a trader can *select* the best offer for a SR, based on dynamic properties of SP offers (according to a predefined selection algorithm), from the set of possible matches. Furthermore, traders can be linked together to form a *federation* [19] in order to provide a wider market for exporters and a greater choice for importers.

4.3.1 Trader service: economic perspective

Trader functionality is an important constituent of an ODS, since it allows SRs to locate a required service (and subsequently set up a contract with the SP) and to dynamically bind to the selected SP, the existence of which they have not known in advance. Hence, the trader is not only important from a technical point of view, but also from a business aspect (as recognised in the corresponding ODP enterprise specification [7]).

The role of the trader is such that it is envisaged it would operate in different organisational settings (both profit and non-profit) as well as across markets, accessible to residential and business customers. The trader's operational mode depends on who *owns* it; an organisation which decides to purchase (a specialised) trader service for its own needs; an owner of a network (carrier) on top of which an ODS is implemented (e.g. part of, or the whole national network); or a third-party service provider [31]. Each of these players will have its own enterprise objectives; these comprise part of the rules of QoS games in which players are SRs, SPs, and the trader owner. Three simple games can be identified: trader owner with SR, trader owner with SP, and SP with SR.

The prevailing factor which decides whether a trader's *user* (either a SR or a SP) will use (hire) some publicly available trader or purchase one, emerges from the spirit of agency theory and transaction cost economics [43]. For example, if a SR is an organisation, it should calculate the sum of costs associated with the trader purchase (capital investment) and subsequent internal agency costs (if any), and compare this with the market transaction costs (these include operational costs, such as search costs, communication costs etc., as well as contractual costs, e.g. costs of writing and enforcing contracts [12]). If the former costs are lower, then the firm should purchase trader. Otherwise, it should use a publicly available trader.

Once these cost considerations are resolved, and the operational setting is decided, it is possible to define the rules of a particular QoS game; they obviously depend on the particular trader's operational environment (e.g organisation or market). We investigate the case of a trader operating in a *market* environment and formulate relevant trader games accordingly.

4.3.2 Agency problems in the context of trading service

Looking at the information structure of trader (TR) QoS games, we will identify information problems related to the quality of TR's service. Several examples of asymmetric information problems in a market setting will be given relating to both TR/SR and TR/SP interactions[17]. For instance, on the TR/SR side, some TR actions, emanating from the owner's policies could be hidden from a *SR* (ex-post situation), which would have an impact on her welfare, e.g.:

- during the import operation, TR does not search through the agreed upon set of SPs (e.g. 'visits' a smaller number of SPs; this may be the case for both matching and selection); the exact TR's search behaviour will be normally hard for the SR to monitor,
- uses random selection, instead of the contracted selection algorithm, which would perform better for the SR,
- fails to match and select with promised accuracy (e.g. does not process search constraints/limitations in the agreed upon way).

On the other hand, the TR owner may have vested interests in certain SPs, or form coali-

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[17] We use the concepts of trader and trader owner interchangeably in this section.

tions with them (ex-ante situation). Hence the TR can engage in information hiding from a *SR*, i.e.:

- favouring particular SPs (e.g. hiding the existence of a more acceptable SP from SRs).

On the TR/SP side, the following *ex-post* situations can arise:

- TR's failure to determine *dynamic* service properties of a SP's service as contracted; thus not supplying up to date information about the SP's state to possible SRs,
- failure to store the updated SP's offer in the trader database.

In addition to these asymmetric information problems, certain parameters related to exogenous uncertainty could also arise (e.g. technological or engineering limitations, increased traffic from other users etc.); hence a whole spectrum of agency problems could occur.

4.3.3 Trading service: abstract formulation in GT setting and concrete example

We will illustrate how trader information asymmetry problems can be modelled and solved with an example of an ex-post QoS game between a TR and a SR. More specifically, we study how the TR's induced effort and the coefficients of a selected payment scheme depend on the data and parameters of the model.

We assume the case of a specialised trader [31], which stores a specific set of service types, e.g. service offers of electronic commerce SPs. We also assume a market structure in which there is a competition between similar trader service providers for gaining a wider market coverage towards both SRs and SPs. This has implications on a SR's and TR's attitude towards risk (as discussed previously) and will be incorporated in a part of our assumption set that follows.

Since the trader service is just another service type, we apply the general model developed in 4.2 to the case of this service; the model is described in terms of relations (1) - (5). However, we still need to select specific forms for: $p(y)$, $U_{SR}(w_{SR})$, $U_{TR}(w_{TR})$, $\tilde{\theta}$, y, and $c_{TR}(x)$. Following previous discussion, we assume the following.

- A linear payment function that a SR offers to the TR, such as one given by (6),
- A *risk-neutrality* of the SR; this implies a linear utility function for the SR.
- A *risk-averse* characteristic of the TR, which can be represented by using an exponential function, e.g. [40]:

  $$u_{TR}(w_{TR}) = -exp(-\alpha_{TR} w_{TR}) \quad , \quad \alpha_{TR} > 0 \tag{7}$$

  where the constant risk aversion factor is:

  $$\alpha_{TR} = -u''_{TR} / u'_{TR} \tag{8}$$

  We note that in the case of utility function (7), the larger this factor, the greater risk aversion. In this specific example we chose a mid-range value for this coefficient., i.e. the TR's constant risk aversion factor $\alpha_{TR} = 0.5$. For a more detailed analysis of the measures of risk aversion in general case, see for example [35].
- The TR provides different options for the search aspect of the trading service, i.e. quality of search (a more detailed treatment of a quality of trading service is given in [30]). For example, the TR can search a different number of trading domains, ranging from a local to a global domain (possibly with a different maximum number of exporters), which requires a different level of 'effort' (measured say, in time units). Formally, we adopt the TR's search action set to be: $x \in X = [0, 1]$, where a larger number from the interval represents a wider search scope, given all other variables are the same. For example, x=1, can mean that the TR agrees to search for a particular kind of the electronic commerce SP at global level. If x=0, the TR will not engage in search at all.
- The TR will engage in search (i.e. accept the SR's offer) only if it can achieve an expected utility greater than its reservation constraint *m*, expressed by (5). Since the parameter *m* relates to the expected utility, its value depends on how this utility is expressed. For example, this can be a monetary value, e.g. the minimum acceptable income. For illustration purposes, we select *m* = 1. In view of the TR's search operation, this can for example correspond to the minimum number of search

domains which will ensure that this constraint is satisfied. However, it could be any other variable, related to the TR's effort.

- The TR's increasing marginal disutility of effort, i.e. the disutility function can be modelled with a quadratic functional form, according to [40]:

$$c_{TR}(x) = x^2 \tag{9}$$

- There is an environmental uncertainty, e.g. the other users' utilisation of TR's resources (e.g. CPU time, database access) and communications resources between TR and the SR, which results in a statistical variation of search response. If the environment between the TR and the SR were deterministic, then the SR would pay to the TR purely on the basis of TR's search effort x. But in the presence of uncertainty, different satisfaction levels of the SR are not only a consequence of TR's effort, but also this exogenous risk. To simplify the illustration, we assume that the only cause of the environmental uncertainty arises due the unpredictable load caused by different users using the underlying ATM network. In this case, the normal distribution can be a good approximation for the search delay, since this variable is reflected by the user load. Statistically, it can be said that there is a series of random processes (i.e. users) on the path between the SR and TR (quite realistic in the case of such a shared environment). According to the central limit theorem, a composition of such processes tends to a normal distribution in the limit. Therefore, we model this risk (state of nature) $\tilde{\theta}$, by using the normal distribution function with the mean delay $E[\tilde{\theta}] = \mu$, and the variance: $Var[\tilde{\theta}] = \sigma^2$.

- Lastly, the outcome $\tilde{y}$, can be expressed as a linear function of the exogenous risk $\tilde{\theta}$, i.e.:

$$\tilde{y} = x + \tilde{\theta} \tag{10}$$

It is known that when the form of the functions which describe principal-agent model have the so called LEN properties [40] (from **L**inear feasible payment scheme and linear risk function, **E**xponential utility and **N**ormal distribution of risk), one can find the exact solution, based on the fact that the certainty equivalents can be expressed as expected value minus half the variance times risk aversion. Now, the first step is a maximisation of $U_{TR}(\tilde{w}_{TR})$ with respect to effort x. Based on (3), (6), and (9) we have:

$$\tilde{w}_{TR}(x,p) = f + s(x + \tilde{\theta}) - x^2 \tag{11}$$

Owing to the LEN properties [40], the derived welfare is:

$$U_{TR}(x, p) = E[\tilde{w}] - \frac{\alpha}{2}Var[\tilde{w}] = f + xs + \mu s - x^2 - \frac{\alpha}{2}s^2\sigma^2 \tag{12}$$

Maximisation of (12) with respect to x yields optimal TR’s response to the payment scheme (6), given by:

$$x* = \frac{s}{2} \tag{13}$$

Hence, TR’s response to the proposed scheme (6) only depends on the share s.

Now, we need to find which payment scheme will be accepted by the TR, in view of the reservation constraint (5). By using (12) and (13), one can find the value for *f*, so that the reservation constraint (5) is satisfied. This gives:

$$f = m - \frac{s^2 \cdot \left(1 - 2\alpha\sigma^2\right)}{4} - \mu s \tag{14}$$

In order to answer the last question, i.e. which payments scheme (6) in terms of its coefficients *f* and *s*, maximizes the SR’s welfare given the TR’s response (13) and fixed fee *f*, one needs to set up the SR’s maximisation problem. Since the SR is assumed to be risk-neutral, and taking into account (4), (6) and (13) the SR will act to maximise:

$$U_{SR}(x*, p) = (1 - s)\frac{s}{2} - f \tag{15}$$

After placing (14) into (15), and maximising (14) with respect to share *s*, we obtain:

$$s* = \frac{1 + 2\mu}{1 + 2\alpha\sigma^2} \tag{16}$$

The optimal fixed part *f* is then obtained from (14) and (16), i.e.:

$$f* = m - \left(\frac{(1 + 2\mu)^2}{(1 + 2\alpha\sigma^2)^2} \cdot \frac{1 - 2\alpha\sigma^2}{4}\right) - \mu\frac{1 + 2\mu}{1 + 2\alpha\sigma^2} \tag{17}$$

Finally, combining (13) and (16), we have:

$$x^* = \frac{1 + 2\mu}{2\left(1 + 2\alpha\sigma^2\right)} \tag{18}$$

Equations (16), (17) and (18), describe the *equilibrium* of this *QoS game,* and thus the *optimal contract* (referred to in AT as the second best agreement) between the TR and the SR.

Now, if an expected delay between the SR's request and TR's response is $\mu = 1$ time units (say ms), and the variance $\sigma^2 = 4$, the TR will take action x = 0.3, the share will be s = 0.6 and fixed fee, f = 0.95. Hence, using the hidden action model of the QoS game between the TR and the SR, and given the forms of characteristic functions, the optimal contract between the TR and the SR would have the form of the following payment function:

$$p(y) = 0.95 + 0.6y \tag{19}$$

and TR's effort,

$$x = 0.3 \tag{20}$$

It is interesting to see how a change in the TR's risk aversion impacts the payment scheme. Let us assume a market structure in which the TR SP is more risk averse, with the risk aversion coefficient of $\alpha_{TR} = 1.0$. When inserting this value into (16) and (17) we obtain *s* = 0.33 and *f* = 0.86. Since the TR was assumed to be more risk averse, it is not surprising that the share *s* is reduced. However, one would expect that the fee *f* should be increased in that case. But this is not the case; this can be explained by the fact that the expression for the fixed payment *f* is a complex function of risk aversion, as well as of mean and variance of the distribution function. It is not unusual in the AT literature to get results which are sometimes not intuitive. This is undoubtedly the consequence of the complexity which is inherent to the AT problem domain.

This simple example illustrates how one can go about designing optimal contracts between a SP (in this case the trader) and a SR, taking into account asymmetric information and uncertainty. We now identify some potential difficulties of this approach in the context of ODSs, and give several future research directions.

4.4 Comments

Following are some comments which refer to different issues addressed in this section.

We begin with a general comment regarding the QoS game, described in 4.2. It is obvious that the SR needs to have some way of *measuring* the outcome *y (*which is basically QoS obtained), in order to be able to determine the actual payment which needs to be transferred to the SP. Hence, one requires an appropriate *QoS metric* as a prerequisite. This metric ought to be *service-independent,* i.e. applicable to a wide range of services available at information markets, e.g a method developed in [29].

One general comment inherent to the complexity of the principal-agent model, needs to be emphasised and recognised in the context of ODSs. The solution of the principal-agent model for the optimal sharing rule in a general setting involves technical issues which are both subtle and profound, as discussed in [5]. Analytical solutions are very rare and can be obtained only by imposing restrictive assumptions on the form of utility functions and probability distribution of the outcome. But because of the usefulness of the principal-agent paradigm and the lack of exact analytical solutions different numerical techniques could be employed to determine optimal contracts [5]. However, these issues are out of the scope of this research.

A related problem is reflected in the method for finding the equilibrium strategies presented in 4.2.4. This method is based on a strong assumption, since it presumes that the principal knows all relevant characteristics of the agent (i.e. utility function, disutility, reservation level, risk aversion factor). As this is hardly realistic in the context of ODSs, and due to the inherent complexity of the problem, some other solution procedures need to be employed through which information about relevant characteristics can be exchanged between users and a system; thus removing the need to have *a priori* knowledge of these. For example, this can be achieved on-line, by employing iterative or hill-climbing methods of solution, in a manner similar to that in [37].

In the trader example, nothing has been said about modelling the SP/TR interaction. This is because there is no essential difference between the TR's interaction with the SR and with the SP in as far as the model of games is concerned. In fact, the only differences are in the TR's QoS attributes delivered to either side, which are catered for in the QoS metrics and in different forms of utility functions, probability distribution and disutility of the SP and the SR. This assumes separability of the trader's functionality with respect to the two types of customers, which is a realistic assumption in the context of open information markets.

It is worth noting that a wider range of information asymmetry situations emerge within the scope of trading. For example, ex-ante agency problems between an owner of a firm (who wants to purchase a trader service) and a trader service provider; different internal agency problems associated with a trader operating in an organisation (especially a large one); and last, but not least, agency problems which arise between SRs and SPs after the trading function has been carried out.

Finally, it is interesting to comment on the extent to which trader owners can exploit previous informational advantage. This depends on the *characteristics of the owner* (e.g. opportunism), but, more importantly, on *environmental factors, e.g.* the number of competitors. It is important to note that, if there are more competitors, agency problems are less severe.

5 Conclusions and future research

We have demonstrated how relevant results of a recent economic theory, agency theory (AT), can be applied to a class of resource problems in open distributed systems (ODSs), which we will confront in the next decade as ODSs are implemented. This is particularly relevant for a set of ODS services which have multiple characteristics and which are non-standard. These resource problems emanate from the existence of different parties each having their own objectives and interacting in the presence of uncertainty. The general analysis of the SP/SR QoS game and the example of a trading service, have illuminated the factors which need to be considered when designing service contracts between players in ODSs. We have shown how information asymmetry problems in ODSs can be taken into account when designing mechanisms for optimal allocation of benefits from using these systems. Our approach represents a generalisation of previous work on applying Game Theory (GT) concepts to different resource problems in telecommunication networks and distributed systems.

The emphasis of this study is on games of asymmetric information; this is pertinent to our view that information asymmetry, so frequent in everyday life, will occur in the context of future ODSs. For example, as information services such as electronic commerce (which have recently started to take place on the Internet) gain momentum, the possibility of trade practice abuses, similar to those occurring in commercial environments, need to be recognised in this new context.

There appears to be a broader scope for future applications of GT to ODSs. Firstly, one can extend present studies to the case of the game set in a multi-player scenario. This will, for example, be of relevance for Computer Supported Cooperative Work (CSCW) applications. As a candidate, AT could provide results from studies of agency problems in a team setting.

Secondly, some concepts from cooperative GT can be applicable for modelling general aspects of federation in ODSs. A particular test example can again be the ODP trader federation concept. This highlights another direction for research, which will look at the function of trader in different organisations, including emerging network organisations which are themselves the product of advances in information technology [6].

Finally, we intend to look at the interrelation between ODSs and economics. While this paper focuses on the applicability of economic disciplines such as agency theory and transaction cost economics to the problem of optimal allocation of resources in ODSs, the opposite direction is also of interest. Namely, information technology is a cause for change in economic organisations (in a broader sense [8]). This is evident in the changing nature of competitive market forces and in the redesign/re-engineering of business processes that many organisations have undergone recently. It is clear that these changes also influence changes in economic theories relating to these fields. It would be interesting to study the role that ODSs can play in these changes.

To summarise, as ODSs develop they will increasingly resemble complex economic systems in which *r*esource sharing takes on new forms and brings novel requirements. One can seek solutions for such problems in contemporary economic disciplines, e.g agency theory, game theory, information economics and contract economics.

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Appendix: basic GT concepts

The essential elements of a game are players, actions, information, strategies, payoffs, outcomes and equilibria[18]. The players, actions and outcomes are collectively referred to as the *rules of the game* [37]. The *players* are the individuals who make decisions, while striving to attain their goals, i.e. to maximise their utility by a choice of actions. *Nature* is a player which is used to represent an exogenous uncertainty, by taking random actions at specified points in the game with specified probabilities. An *action* or *move* by a player is a choice he can make.

An *extensive form* of game can be used to represent complex games in which the order of moves is important and where some actions are not instantly observed by every player - the scenario indeed applicable to ODSs. This form uses *game tree* representation, whereby nodes of the tree represent points in the game at which some player or Nature takes an action, or the game ends (outcomes of the game). A *branch* is one action in a player's action set at a particular node.

Players*' information* at any particular point in the game is modelled using the concept of the *information set*. This is defined as the set of different nodes in the game tree that the player knows might be the actual node, but between which he cannot distinguish by direct observation. If the information set has many elements, there are many values that the player cannot rule out; if it has one element, he knows the values precisely. A player's *strategy* is a rule that tells him which action to choose at each instant of the game, given his information set. A *strategy combination* is an ordered set of one strategy for each of the players in the game. A player's *payoff* is the *utility* he receives after all players and Nature have picked their strategies and the game has been played out. The *outcome* of the game is a set of interesting elements that the modeller picks from the values of actions, pay-offs, and other variables, after the game is played out.

An *equilibriu*m is a strategy combination consisting of a best strategy for each of the players in the game. A *solution (equilibrium) concept* is a rule that defines an equilib-

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[18] This text is based on [34].

rium based on the possible strategy combinations and the payoff functions. Two of the best known solution concepts are *dominant strategy* and *Nash equilibrium*.The strategy is *dominant* if it is a player's strictly best response (i.e. the strategy, that yields him the greatest payoff) to any strategies the other players might pick; a *dominant strategy equilibrium* is a strategy combination consisting of each player's dominant strategy. Since very few games have a dominant strategy equilibrium, a more widely accepted equilibrium is Nash equilibrium. The strategy combination is a *Nash equilibrium* if no player has the incentive to deviate from his strategy, given the other players do not deviate.

The *information structure* of a game can be categorised in four different ways, i.e. games with perfect, complete, certain and symmetric information. In a game of *perfect information* each information set is a singleton. Otherwise the game is one of *imperfect information*. In games with perfect information, each player always knows where he is in the game tree, no moves are simultaneous and all players observe Nature's moves; thus, the strongest informational requirements are met in this game. A game of *certainty* has no moves by Nature after any player moves. Otherwise the game is one of *uncertainty*. Under uncertainty, the model used to evaluate players' uncertain future pay-offs is based on maximising the *expected* values of their utilities. In games with *incomplete information*, a player does not know the precise types of the other players; otherwise the game has complete information. Games with incomplete information are represented by letting Nature move first, choosing the *type* of each player (i.e. the strategy set, payoff function etc.). This first move of Nature is referred to as its choice of *state of the world*. In a game of *symmetric information*, a player's information set at any node where he chooses an action, or at an end node, contains at least the same elements as the information sets of every other player. Otherwise, the game is of *asymmetric information*.