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A game-theoretic approach for the web services scheduling problem

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ABSTRACT

We address the design of an Internet-based business process composed of several web services by using multiobjective optimization and game-theoretic methods. Adopting a suitable representation for the business process, we present a mathematical optimization problem which considers several quality-of-service objectives: cost, execution time, reliability, availability and reputation. The web service scheduling problem is formulated as a multiobjective mixed-integer linear optimization problem and solved through a goal optimization method. The optimal solution of the scheduling problem assigns suppliers to all the tasks that comprise the business process, thus establishing the revenues – utilities – of all the suppliers. We then model the interaction between the suppliers as an incomplete information (Bayesian) game: the structure of the game is common knowledge of all the suppliers, but each supplier knows only his/her own utility function. A characterization of the Bayes–Nash equilibria of the game is provided. The paper includes numerical examples.

1. Introduction

A typical Internet-based business can be thought as composed of several web services to be supplied by partners with basis in Internet technologies. The web service scheduling problem attracted considerable interest in the last decade (Ardagna & Pernici, 2006; Fan, Fang, & Jiang, 2011; Liang & Huang, 2009; Parejo, Segura, Fernandez, & Ruiz-Cortés, 2014; Rodriguez-Mier, Mucientes, Vidal, & Lama, 2012; Zeng et al., 2004). Nowadays, web service technologies support applications in finance (Chen, Zhou, & Zhang, 2006), manufacturing (Tao, Zhao, Hu, & Zhou, 2010), supply chain (Smeureanu, Ruxanda, Diosteanu, Delcea, & Cotfas, 2012) and cloud computing (Qi, Dou, Zhang, & Chen, 2012), among others.

A composite web service system may be structured in terms of the following components (Zeng et al., 2004): a set of web services; a *service broker*, which allows web suppliers to describe their services – capabilities and quality-of-service (QoS) attributes – in a UDDI (Universal Description, Discovery and Integration) registry; a *service manager*, made up of an *execution planner*, which, by using information (candidate web suppliers) retrieved from the service broker, assigns web suppliers to tasks of the composite web service, and of an *execution engine*, which coordinates the system components to execute, at runtime, an instance of the composite web service.

The composite web service associated to a generic business process is specified as a collection of tasks with control-flow and data-flow dependencies. The present paper focuses on the business process scheduling problem faced by the execution planner, understood as the problem of assigning suppliers to tasks guided by constraints and preferences formulated in terms of QoS attributes, as execution time, cost, service reputation, reliability and availability of the service. Dependencies between tasks are represented in the Business Process Modelling Notation (BPMN) (Chinosi & Trombetta, 2012), and then as a directed graph, more convenient for mathematical modeling and computational purposes.

An efficient resolution of the web service scheduling problem has a huge impact on global performance of the business process. An efficient execution plan guarantees that the constraints and preferences of the users are taking into account, which is the most important factor to ensure costumer satisfaction. By efficiency we mean an optimized use of the available resources subject to constraints and preferences. As the number of alternatives (web services and their QoS attributes) for the composite service can be very large, different approches for solving the web service scheduling problem have been proposed.

The literature on web service composition distinguishes between local and global approaches (Strunk, 2010). The former assigns the best candidate service that supports the execution of the running task; the latter determines the best set of candidate

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services that supports the execution of the composite web service. Best candidates, at local and global level, are selected considering QoS attributes.

It is generally admitted that local approaches do not effectively integrate QoS specifications – the execution time of the composite service may be limited to a given value, or the total cost may not be allowed to exceed a prescribed budget – and the preferences of the business designer. On the other hand, global approaches, as the ones proposed in this paper, are more demanding in terms of computational infrastructure.

A mathematical programming framework for the web service scheduling problem was proposed in Zeng et al. (2004) and refined in Ardagna and Pernici (2006). The service composition problem is modeled as a multiobjective mixed-integer linear optimization problem, which is then solved by exact methods of Integer Programming (Wolsey, 1998). However, as the service scheduling problem is, regardless the mathematical model (linear or nonlinear) adopted, a difficult combinatorial problem, solutions based on exact methods eventually become impractical for instances with large numbers of web services or composite tasks. This computational aspect of the problem has motivated the proposition of a number of metaheuristic approaches, as Genetic Algorithms, Simulated Annealing, Tabu Search, GRASP and Path Relinking (Gendreau & Potvin, 2010).

Bio-inspired algorithms are surveyed in Wang, Shen, and Yong (2012). The use of Genetic Algorithms was proposed in Canfora, Penta, Esposito, and Villani (2005), and subsequently improved by several authors in the way of encoding information and handling population diversity (Gao, Cai, & Chen, 2007; Ma & Zang, 2008; Su, Ma, Guo, & Sun, 2014; Wada, Suzuki, Yamano, & Oba, 2012). The use of Simulated Annealing was proposed in Wang, Tong, Thompson, and Li (2007). Algorithms which combine Simulated Annealing with Tabu Search and with Particle Swarm Optimization (Kennedy & Eberhart, 1995) are proposed in Ko, Kim, and Kwon (2008) and Fan et al. (2011), respectively. Particle Swarm Optimization is also used in Fan (2013) for approximating Pareto-optimal execution plans in multiobjective service composition problems. The use of GRASP has been recently applied to the problem of determining the adaptations that minimize the total cost incurred by the violation of service level agreements (Leitner, Hummer, & Dustdar, 2013). Finally, Parejo et al. (2014) combines GRASP with Path Relinking for composing web services at runtime.

When focused on the business process point of view, the literature shows a progressive emphasis in modeling the competitive relationship between web service suppliers by using concepts and methods of Game Theory (Shoham & Leyton-Brown, 2009). Sun et al. (2006) considers coalitions formed by web suppliers and consumers, and proposes a Core-based solution to regulate the market; Shen and Fan (2007) addresses time-sensitive services and proposes a cooperative mixed-strategy approach to reach an equilibrium point of the noncooperative game played by the users of the service; Li (2011) develops a mathematical model for describing the conflict between concurrent tasks and their impact on the performance of the composite service. The proposed algorithm, which reaches a Nash equilibrium in terms of task utilities, is applied in Li, Zhu, Yang, and Xu (2012) to a remote sensing service composition problem; Khosravifar et al. (2013) presents a two-player game-theoretic model in which an individual web service (player 1) can either act alone or cooperate with a community of web services (player 2). The authors investigate the conditions under which the utilities of the players are maximized.

An analysis of the literature on web service scheduling reveals that the global approches that model QoS attributes as multiple objectives to be optimized either develop a search for the whole set of Pareto-optimal execution plans (as in Wada et al. (2012) and Fan (2013)), without specifying an actual execution plan, or aggregates the objectives in a presumed utility function. On the business process side, an approach that integrates game theoretic and multiobjective optimization scheduling models seems to be needed.

With the present paper we aim at advancing the current state-of-art in methodologies for web service composition with two innovations:

(i) Following the mathematical programming framework introduced by Zeng et al. (2004) and Ardagna and Pernici (2006), we formulate the web service scheduling problem as a multiobjective mixed-integer linear optimization problem (Collette & Siarry, 2011; Wolsey, 1998). However, instead of aggregating objectives (minimize execution time and cost, maximize reputation, reliability and availability) into a presumed utility function, we propose a goal programming approach. By using this approach, preferences about the objectives are expressed in terms of goals to be pursued and suppliers are assigned to tasks in order to minimize the deviations from these goals. The optimal solution of the scheduling problem assigns suppliers to all the tasks that comprise the composite service, thus establishing the revenues (utilities) of all the suppliers;

(ii) The interaction between the suppliers is modeled as a non-cooperative, incomplete information (Bayesian) game (Shoham & Leyton-Brown, 2009). The structure of the game is common knowledge of all the suppliers, but each supplier knows only his/her own utility (revenue) function. The Bayes–Nash equilibria of this game establish the strategies (in terms of expected utilities) that the suppliers should adopt while competing for the tasks of the composite service. The characterization of the Bayes–Nash equilibria of any game is a fundamental step towards more refined models for the interaction between players, particularly in the Mechanism Design domain (Narahari, Garg, Narayanam, & Prakash, 2009).

We solve every single objective optimization problem that results from the goal programming formulation using the mixed-integer (exact, branch-and-cut) optimization routine of the GLPK package (Gnu Project, 2012), a very efficient routine for small and medium scale instances. Large scale instances may require the use of metaheuristics. The Nash equilibria of the normal form game induced by the Bayesian game between web service suppliers are obtained using the vertex enumeration algorithm presented in Avis, Rosenberg, Savani, and von Stengel (2010). The paper includes simulation results obtained through the utilization of the modeling approaches proposed.

The paper is organized as follows. In Section 2 (Methods) we outline the mathematical model of the web services scheduling problem, detail the composite web service objectives and constraints, formulate the problem within a goal programming framework, and model the interaction between web suppliers as a non-cooperative, incomplete information (Bayesian) game. In Section 3 (Results and discussion), the effectiveness of the goal programming and game theoretic approaches are numerically investigated through simulation. In Section 4 (Related work) we compare our contributions to some alternative approaches. Conclusions and future research directions are presented in Section 5.

2. Methods

Business processes can be represented by using the Business Process Management Notation (Chinosi & Trombetta, 2012). Some