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Self-regulating supply–demand systems

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HIGHLIGHTS

- Internet of Things technologies enable an automated, online and bottom-up regulation.
- A decentralized self-regulatory framework for supply–demand systems is proposed.
- A evaluation methodology allows the systematic assessment of optimality.
- Higher informational diversity in agent selections result in higher performance.
- Agents' selection strategies show striking measurable performance trade-offs.

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ABSTRACT

Supply–demand systems in Smart City sectors such as energy, transportation, telecommunication, are subject of unprecedented technological transformations by the Internet of Things. Usually, supply–demand systems involve actors that produce and consume resources, e.g. energy, and they are regulated such that supply meets demand, or demand meets available supply. Mismatches of supply and demand may increase operational costs, can cause catastrophic damage in infrastructure, for instance power blackouts, and may even lead to social unrest and security threats. Long-term, operationally offline and top-down regulatory decision-making by governmental officers, policy makers or system operators may turn out to be ineffective for matching supply–demand under new dynamics and opportunities that Internet of Things technologies bring to supply–demand systems, for instance, interactive cyber–physical systems and software agents running locally in physical assets to monitor and apply automated control actions in real-time. e.g. power flow redistributions by smart transformers to improve the Smart Grid reliability. Existing work on online regulatory mechanisms of matching supply–demand either focuses on game-theoretic solutions with assumptions that cannot be easily met in real-world systems or assume centralized management entities and local access to global information. This paper contributes a generic decentralized self-regulatory framework, which, in contrast to related work, is shaped around standardized control system concepts and Internet of Things technologies for an easier adoption and applicability. The framework involves a decentralized combinatorial optimization mechanism that matches supply–demand under different regulatory scenarios. An evaluation methodology, integrated within this framework, is introduced that allows the systematic assessment of optimality and system constraints, resulting in more informative and meaningful comparisons of self-regulatory settings. Evidence using real-world datasets of energy supply–demand systems confirms the effectiveness and applicability of the self-regulatory framework. It is shown that a higher informational diversity in the options, from which agents make local selections, results in a higher system-wide performance. Several strategies with which agents make selections come along with measurable performance trade-offs creating a vast potential for online adjustments incentivized by utilities, system operators and policy makers.

1. Introduction

Regulating supply–demand systems in techno-socio-economic sectors of Smart Cities, such as energy, transportation, telecommunication, financial markets and others, is a complex, yet critical endeavor for societal development and sustainability. Regulation

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usually implies government-imposed controls on business activities and infrastructural operations [1], in which decision-making by the involved actors is often centralized and operationally offline. However, the introduction of Internet of Things technologies [2] to tackle the inter-temporal nature of supply and demand [3] creates a vast potential for an automated, online and decentralized self-regulation using remotely communicating sensors, controllers and actuators. For example, the regulation of electricity prices used to be a result of institutional and legal policy designs strictly imposed in a top-down fashion. In contrast, Smart Grid technologies enable regimes within which bottom-up price formation can be automated via real-time pricing schemes and tariffs that continuously balance supply and demand [4–8].

This new type of online bottom-up self-regulation imposes two grand scientific challenges: (i) How to effectively balance supply and demand in different regulatory scenarios by steering the price elasticity of demand in a fully decentralized fashion? (ii) How to continuously measure and evaluate this self-regulatory capability in different regulatory scenarios of supply–demand systems? Regulatory scenarios refer to the mitigation of imbalances in supply–demand originated from varying generation and/or consumption, system failures, system reforms, etc. This paper studies the balance of supply and demand with a fundamental, yet highly applicable, approach by introducing a minimal and standardized information exchange. This approach does not require major system interventions and can make a self-regulation mechanism applicable in various Smart City sectors.

How to balance supply–demand or how to design efficient computational markets remains a fascinating challenge for a very broad range of scientific communities. Most remarkably, game-theoretical approaches in combinatorial games are relevant in systems in which agents have a finite number of options to choose from and each choice influences the evolution and outcome of the game. Although mathematical tools exist for solutions to particular problems [9], there is no unified theory or framework addressing combinatorial elements in these games. This observation usually characterizes matching mechanisms [10] and learning techniques that have at least the following limitations in applied contexts: (i) long convergence times [11,12] that can make them inapplicable in practice due to technological limitations, e.g. communication bandwidth or computational capacity. (ii) Solutions have often a limited scope, meaning that equilibrium is not guaranteed with a minor problem modification or when adding/removing a constraint [13]. For example, the literature on certain game-theoretical approaches in Smart Grids reveals the limited applicability of cooperative games and dynamic models to tackle the pervasive presence of time-varying parameters such as generation and demand [13]. Moreover, it is also shown that network delays may lead to incorrect price inquiries. A similar conclusion is shared within other related work [14] claiming that a highly responsive and non-disruptive regulatory system for load requires direct centralized control by utilities [14]. There is recent ongoing work to tackle these challenges [8], however, it remains an open question how fully decentralized coordination mechanisms can operate without relying on central broker entities or assuming global/aggregate information available locally.

This paper contributes a novel and generic self-regulatory framework for supply–demand systems. A single-commodity resource-oriented equilibrium market [10] resembles the operations of the proposed self-regulated supply–demand system that interacts with a loop of (i) incentive signals that communicate supply costs and (ii) feedback signals that communicate the demand acquired. Agent-based bilateral interactions are performed in the background of a bottom-up computational mechanism advanced to operate in this generic context of distributed supply–demand systems. This mechanism self-regulates the balance of supply and demand in a similar fashion with the intuitive paradigm of Adams Smith's 'invisible hand' [15]. Regulation becomes an emergent system property [16], originated from reconfigurable interactions and adaptive decision-making structured over a self-organized tree topology. Earlier work motivates the adoption of tree structures in computational markets and supply–demand systems [17–19], however, the proposed framework does not exclude the adoption of other mechanisms and structures [20].

Evidence using real-world datasets of energy supply–demand systems confirms the effectiveness and applicability of the framework in a broad spectrum of regulatory scenarios. The implications of informational diversity in consumers' options but also the actual consumers' selections are studied by quantifying the regulatory capability with two metrics referred to as 'response' and 'savings'. A novel characteristic of these metrics is that they are relative to different upper bounds. This allows the systematic evaluation of optimality and constraints resulting in more informative and meaningful comparisons of different self-regulatory settings. Findings show measurable trade-offs between response and savings creating a vast potential for online adjustments incentivized by utilities, system operators and policy makers.

2. Self-regulatory framework

In this paper, a *self-regulated supply–demand system* is defined by the inner operational system capability of distributed producers and consumers to collectively coordinate their actions remotely based on a fully decentralized computational design such that supply and demand are met under different regulatory scenarios. This section introduces a self-regulatory framework for supply–demand systems. It is shown how this framework can be realized as a decentralized transactive control system that is a well-established standardized concept and implemented technology in real-world supply–demand systems of Smart Cities. Table A.1 in Appendix A outlines all mathematical symbols used in this paper in the order they appear.

2.1. Overview

The studied supply–demand system consists of communicating (software) agents that represent or control the actions of producers and consumers, for instance, smart meters in smart grids or vehicles in transportation systems. Communication between agents can be performed over the Internet or via other dedicated communication infrastructures of certain supply–demand systems [21], for instance, a SCADA system in smart grids. The agent facilitates the self-regulation logic and represents social or operational requirements such as the type/amount of resources supplied and demanded. Depending on how a supply–demand system is institutionalized, three modes of self-regulation can be applied: (i) *demand-side*, (ii) *supply-side* and (iii) *supply–demand-side*. The demand-side mode assumes the production of resources is given by system operators and consumers need to adapt to the available supply. Respectively, the supply-side mode assumes the demand of consumers is given by system operators and production needs the adapt to the formed demand. Finally, in the supply–demand mode, none of supply or demand are given and they are both formed interactively. Due to space limitations, this paper mainly focuses on the first two self-regulation modes. For consistency and an intuitive understanding of the framework, the rest of this paper illustrates the framework from the viewpoint of self-regulation in demand-side mode. Fig. 1 introduces an overview of the framework.

Self-regulation aims at balancing supply and demand under various operational scenarios and constraints, such as keeping demand within a certain range, distributing demand fairly among