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District Information Modeling and Energy Management

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For smart cities, information from different data sources must be integrated into a common digital archive. DIMMER is a distributed software infrastructure for information modeling and energy management that correlates such information with user behavior patterns and feedback.

For the smart city vision to move forward, ICT must be a key player¹ in enhancing energy optimization in cities.² At the building level, monitoring and control solutions have been developed along with user-awareness policies to promote green behaviors.³ Real-time information about environmental characteristics and energy consumption can be accessed from pervasive devices deployed in a building. At the district level, information about heating distribution networks and the power grid can be accessed by sensor networks. In this context, heterogeneous devices are involved in the monitoring and management processes of buildings and grids.

Facilitating information exchange between these heterogeneous devices is an issue that can be overcome thanks to middleware technology. Indeed, middleware can help enable interoperability across heterogeneous data sources, either hardware or software, and provide an abstract view of their functionalities. Once interoperability is enabled, information from these data sources can be collected and correlated into a common and distributed “smart digital archive” for managing energy in the district. In this scenario, different stakeholders in the smart city context can access this information or push new data. Moreover, the ICT revolution in *building information modeling* (BIM)⁴ enables the digital organization of building characteristics and parameters. Hence, making district energy production and consumption data available to client application and control policies jointly with BIM information would increase energy efficiency at the urban level. For instance, better-performing policies can be developed that take advantage of building performance and characteristics. In addition, providing such information to client applications would increase user awareness about energy-consuming behaviors. Furthermore, feedback from citizens can be collected for a better understanding of users’ behavior patterns, which can then be considered when improving energy policies at the district level.

All this information enables new business models for different actors in the smart city scenario. Hence, a distributed architecture is needed that focuses on

- enabling interoperability among district energy production and consumption, environmental data (such as air temperature or relative humidity), and user feedback data;
- integrating BIM 3D parametric models with real-time data;
- providing pervasive and real-time feedback about the energy impact of user behavior; and
- allowing new business models.

The District Information Modeling and Management for Energy Reduction (DIMMER) platform is a distributed software infrastructure that creates a district information modeling and simulation framework that can collect, process, and remotely visualize district-level energy usage and the structural parameters of buildings and systems. DIMMER also promotes information exchange between different actors in the district, exploiting a Web services approach. It collects real-time monitoring information sent by heterogeneous sensors installed in buildings and along distribution networks (such as heating and power networks). The energy-related data can be correlated with BIM 3D parametric models and enriched with feedback from various users. At the core of the system, a processing engine elaborates input data to provide energy-positive and economically suitable actions to users. Furthermore, thanks to Web service interfaces, policies can be developed to monitor and control energy consumption and production from renewable sources. DIMMER allows user applications to access energy-related information for energy and cost analysis, tariff planning and evaluation, failure identification and maintenance, and information sharing. Exploiting this infrastructure, a district could reduce both energy consumption and CO₂ emissions by enabling more efficient energy distribution policies that are in line with the real characteristics of its buildings and inhabitants.

DIMMER Infrastructure Requirements

The DIMMER software infrastructure needs to interface building information with district energy distribution network models and to integrate real-time data from pervasive devices at the network and building levels. This information is enriched with user profiles as well as feedback from local residents.

To achieve this, we developed the DIMMER architecture with the following requirements in mind.

Real-Time Data Collection

The platform must exploit real-time data from various sensors (that is, smart meters and environmental sensors) to provide actual information about building usage and thermal characteristics.

Advanced Middleware Technology

The software architecture needs to integrate different monitoring systems that exploit middleware technologies to enable interoperability across heterogeneous devices and abstract these devices' functionalities.

Asynchronous Communication

The software infrastructure must implement asynchronous communication by exploiting the publish-subscribe approach,⁵ which complements the request-response approach. The publish-subscribe paradigm increases scalability because it removes interdependencies between information producers and consumers, allowing the development of services independent from the systems and deployed devices. Furthermore, it enables the development of distributed services that can react in real time to certain events.

User and Social Profiling

The platform must collect user feedback and actions and use them to build social behavior models to foresee user attitudes and energy demand.

Energy Efficiency and Cost Analysis Engine

Exploiting real-time information from devices in buildings, from district energy distribution networks, and from BIM models and user behaviors enables the energy efficiency engine to compute optimal demand response and energy distribution. Depending on the type of building and possible actuations, the output of this analysis can be used to suggest energy-saving actions to users or actuate optimized distribution policies. The analysis engine will also be able to suggest more suitable behaviors by accounting for variable tariffs.

Web Interface and Interaction

The platform needs to provide tools and Web services for developing user applications to show information about energy consumption and promote green behaviors. Through such applications, some actions to improve energy efficiency can be suggested in real time, and feedback from users can be collected.

Software Infrastructure

The DIMMER platform is a distributed software infrastructure built on top of LinkSmart middleware (<https://linksmart.eu/redmine>), which provides features for enabling interoperability across heterogeneous devices by creating a peer-to-peer (P2P) network. LinkSmart also provides features and software components to enable secure and trusted communications,⁶ controlling whether a device or service can be trusted. Therefore, it enables mutual authentication by providing the means to create a public-key infrastructure. Furthermore, it allows cryptographic operations for message protection to guarantee confidentiality between parties.

As shown in Figure 1, DIMMER is a three-layered architecture consisting of a *data-source integration layer*, *district services layer*, and *application layer*. Communication among the different layer components exploits both request-response and publish-subscribe paradigms, with either a P2P or client-server network topology.

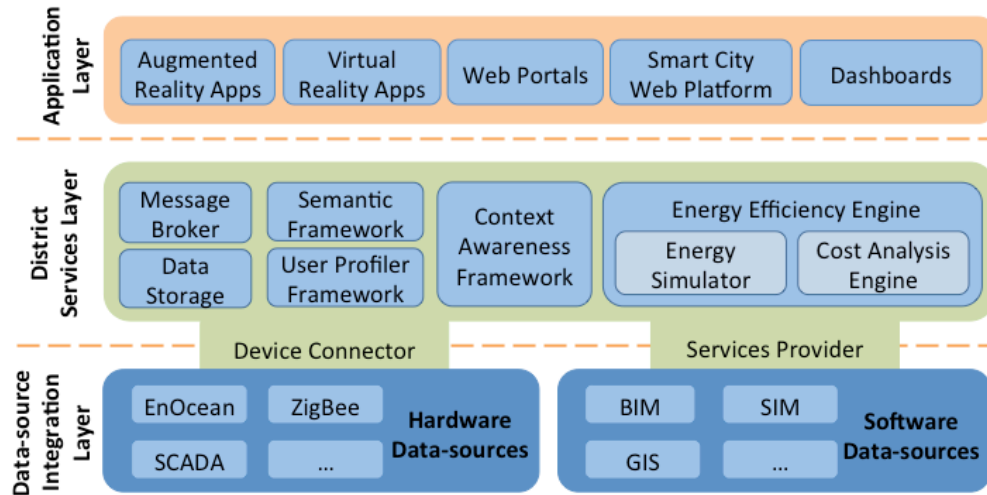


Figure 1. Schema of the DIMMER software infrastructure. The architecture consists of three layers and exploits both request-response and publish-subscribe paradigms.

Data-Source Integration Layer

The data-source integration layer enables interoperability across heterogeneous technologies, both hardware and software. Such interoperability is achieved thanks to two LinkSmart components: the *device connector* and the *services provider*. The device connector abstracts a certain device by translating whatever kind of language the low-level technology is characterized as into Web services. The service provider integrates different software data sources. Within the DIMMER architecture, the provider exports information about BIM, GIS, and system information modeling (SIM) via Web services. Hence, other DIMMER applications can exploit information about 3D building parametric models, which can be coupled with the district energy system models (such as energy distribution networks) and enriched with geo-referenced data.

District Services Layer

The district services layer is the core of the DIMMER architecture and includes different middleware-based components for providing services at the district level.

Message broker. The message broker is responsible for providing asynchronous communication, exploiting the MQTT communication protocol that implements the publish-subscribe approach.⁵ Hence, each device or component in the DIMMER platform can publish information, and other subscriber applications can receive it independently. Note that the device connector also exploits message broker services to send data in real time. The message broker also increases the scalability⁶ of the whole infrastructure.

Data storage. This service collects the data coming from pervasive devices deployed across the district. The DIMMER platform can also integrate already existing databases—for instance, those owned by energy providers, municipalities, or other actors.

Semantic framework. The semantic framework exploits Semantic Web technologies to provide a semantic description of the entities in the district, enriched with additional attributes and relations to other entities. The DIMMER ontology includes metadata about domains and objects involved at the building, distribution network, and district levels. These nodes are linked with deployed devices (sensors and actuators) that are described in terms of hardware capabilities and measured physical parameters. Energy profiles for buildings are described as well. Semantic knowledge is stored in a Resource Description Framework (RDF) database management system and can be queried and manipulated through SPARQL. Hence, any kind of information, such as a sensor's location or capabilities, a list of all sensors in a building, or a building with a specific load profile, can be queried from a rich domain model.

Context-awareness framework. This framework provides applications with features for modeling real-world situations by defining a set of properties as contexts. For instance, by exploiting this component, such applications can get notifications when those contexts are matched or their states change.

User-profiler framework. This service collects user actions and feedback to profile and predict human behaviors related to energy behavioral patterns. These data are useful for quantifying possible improvements that can be obtained if energy consumption profiles change.

Energy efficiency engine. The energy efficiency engine consists of two submodules, the *energy simulator* and the *cost analysis engine*. They exploit data from other DIMMER components and from the data-source integration layer to simulate energy optimization policies and provide an evaluation of such policies' economic impacts. In addition, the cost analysis engine can suggest more suitable behaviors by accounting for variable tariffs. As regards energy optimization, control policies at the building and district levels can be developed. These policies can exploit historical and real-time data from buildings and energy distribution networks correlated with their BIM and SIM models.

Application Layer

The application layer provides a set of APIs and tools to manage and post-process the information coming from the lower layers. At this layer, different applications can be developed to provide information with different granularity. We identified three layers of detail: The *people level* includes applications for providing suggestions to users and for collecting feedback from citizens to profile their behavior patterns. The *building level* represents all applications that provide information and suggestions about a building as a whole. The *district level* includes applications for monitoring and managing the whole district.

Case Study

To evaluate the proposed infrastructure, we deployed a prototype DIMMER platform, selecting as a case study a district in Turin, Italy. In this district, the IREN heating distribution network serves roughly 50 percent of the public and private buildings. IREN is a multi-utility company operating in the electricity and thermal-energy sectors to provide district heating (www.gruppore.it/index.asp). To monitor the thermal energy of the heating network and heat exchanger in the buildings, around 4,000 sensor devices are deployed. Every five minutes, they collect information such as instantaneous power, cumulative energy consumption, water flows, and corresponding temperatures. This information is sent via embedded gateways that monitor the heat exchangers. Each gateway is equipped with a GPRS modem, and is in charge of executing the following tasks: sensor management, data collection scheduling, GPRS communication, and sending collected data to a remote DIMMER data storage unit deployed at an IREN datacenter. To guarantee system reliability and scalability, each data frame sent by gateways is assigned to one of four dispatchers. Then, each dispatcher delivers the data frame to a cluster of databases to store it.

For the selected district, geo-referenced information is provided by CSI Piemonte (www.csipiemonte.it/web/en/), a consortium that implements and manages ICT services for Piedmont's public administration. In addition to GIS Web services, CSI also provides the SIM models of the IREN district's heating network.

Finally, six buildings have been selected as representative for their orientation, dimension, use, materials, and construction period. These buildings have been modeled by exploiting the BIM methodology. The BIM parametric models are shared in the DIMMER platform through the *services provider*, which is deployed on the Politecnico di Torino campus, in three different formats: JavaScript Object Notation (JSON), Industry Foundation Classes (IFC), and Green Building XML (GBXML). To monitor the indoor air temperature and relative humidity in each of these buildings, we deployed a wireless sensor network managed by an embedded PC. Such data are sent to a data storage unit deployed on our campus. The *device connector* integrates these devices into the DIMMER infrastructure.

Impacts on Energy Efficiency

The European Commission (EC) has a set of policies for developing EU strategies to promote ICT for energy efficiency in buildings (<http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>). The DIMMER software infrastructure fosters the extension of near-zero-energy building strategies at the district level, given that near-zero-

energy districts are the next frontier in energy efficiency and sustainability.

The proposed solution aims at making the energy demands of buildings rational, which involves optimizing load profiles and set points. This is expected to facilitate a load shift and a reduction in the energy requests of buildings. The positive impacts for producers are represented by the reduction in peak requests and the optimization of demand response. This allows new users to connect to the energy distribution network, even in saturated areas. The positive effects for users are a reduction in total energy demand and the potential to shift part of the hourly load as realized through lower energy costs.

Following the case study described in the previous section, the energy performance in the district heating network can be enhanced by exploiting the DIMMER infrastructure. In this scenario, the new policies take into account information coming from four different sources: pervasive devices in the district, structural data and thermal models from BIM, district heating network technical properties and layouts from SIM, and user behavior patterns from the user profiler framework. Correlating all this information using a common infrastructure can help improve heating demand management. The output of the new policies includes improvements deriving from an optimized energy utilization schedule and incentives to change user behaviors to modify users' thermal profile curve.

The Turin district heating network provides heat to about 5,500 buildings. Heat is produced using large, efficient plants, such as combined cycles and industrial boilers. In particular, the combined cycles can produce electricity and heat at the same time (cogeneration), which enables really efficient fuel use. Using these cogeneration systems, the primary amount of energy necessary to produce a unit of heat is about 0.36 MWh/MWh. The total heating power that can be produced by the three combined cycles that are installed is about 780 MW. Even though industrial boilers are more efficient than those usually installed in buildings, they are much less efficient than cogeneration plants. The primary energy necessary to produce a unit of heat is about 1.11 MWh/MWh. For this reason, boilers are used to cover the portion of the thermal request that exceeds the cogeneration capacity.

To show the possible impact of variations in a district's thermal load profile, we consider a thermal barycenter of the Turin district heating network. A barycenter connects a cluster of buildings (on average 50) geographically close to each other to the district heating network backbone. The considered district is characterized by a thermal request of roughly 30 MW. We compare two scenarios: the original thermal request and the modified thermal request. In the second scenario, the buildings' thermal request profiles are shifted in time to fulfill the requirement that the average temperature be maintained at the level corresponding to scenario 1 at 7 a.m. This temperature is estimated using a model of the buildings, which is fed with real temperature measurements at the heat exchangers.

Figure 2 shows the original thermal request (solid line) and the modified request (dashed line) for the thermal plants feeding the district heating network on a typical day during the heating season. Note that applying the modified thermal request profile makes the total thermal request increase between approximately 3 a.m. and 5 a.m., and decrease between approximately 5 a.m. and 7 a.m. Positive impacts on primary energy consumption include a net increase in the thermal load when total thermal power is below 780 MW (that is, cogeneration capacity); and a net reduction in thermal load when total thermal power is above 780 MW. This translates into a net increase in cogeneration use, which enables a reduction of about 80 MWh/day in primary energy consumption for heating.

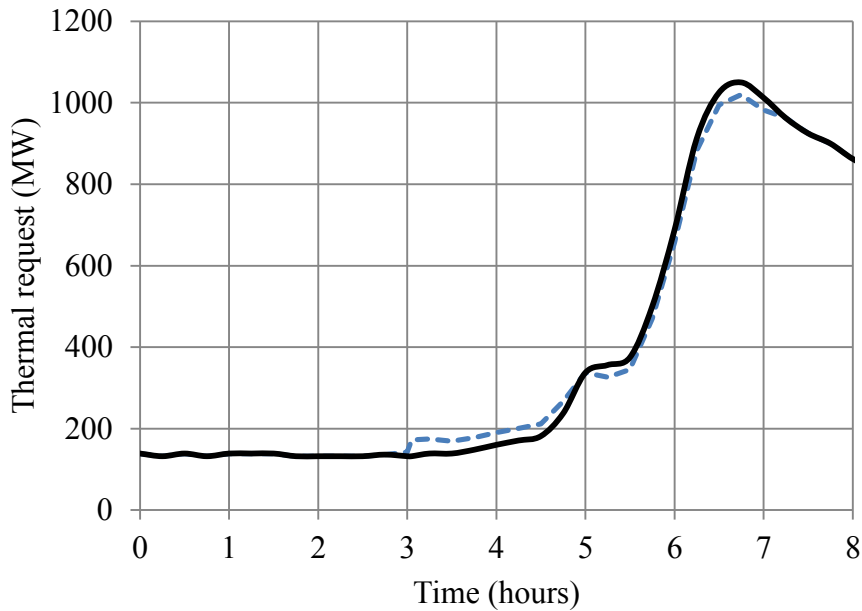


Figure 2. Load profile for the thermal plant applying two thermal profiles for users. We compare the original thermal request (solid line) and the modified request (dashed line) for the thermal plants feeding the district heating network on a typical day during the heating season.

Note that in this work, our case study focused on a specific district in Turin, and we show results on thermal-energy optimization. However, the DIMMER infrastructure can also process information from the power grid. Hence, the same platform can be used to improve demand response in power systems, taking into account renewable plants.

New Business Opportunities

The DIMMER platform aims at creating a distributed, smart digital archive of a city, in which different actors in the smart city scenario can publish and use (if authorized) different information to provide innovative services. Following this view, the different data sources can be integrated in the DIMMER infrastructure.

New and emerging building design techniques exploit the BIM methodology. Hence, public administration can convert its cadastral maps into more accurate digital BIM parametric models, creating new business opportunities. BIM models are also used to perform energy simulation for the building itself. Therefore, to reduce energy consumption, the DIMMER platform can provide suggestions for refurbishment actions and a related cost analysis. Similarly, energy distribution networks can be digitized into SIM models. Hence, public administration can provide such parametric models together with GIS information to authorized users exploiting the DIMMER platform.

The energy market comprises different actors (for example, retailers, energy providers, or energy service companies) that can share their information by, for instance, integrating their already deployed sensors or databases into DIMMER. Therefore, having a complete overview of energy consumption and production in the district, and taking into account BIM, SIM, and GIS information, more efficient control policies can be developed to improve demand response. Finally, another business opportunity is to promote suitable tariffs by providing new services for the remote management of smart appliances to again improve demand response.

Finally, with the information provided by the DIMMER platform, applications as a service can be developed for professionals who manage buildings and districts. End user applications can also be developed to increase awareness about energy consumption, thus educating users about green behaviors.

DIMMER's smart digital archive is unique for cities and is a useful support for developing strategic plans in the city

itself. We presented a case study based on the district-heating network. In future work, we plan to exploit the DIMMER infrastructure for processing information from power grids and simulating new demand-response strategies, also considering renewable power systems.

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