THEME ARTICLE: IoT-Enhanced Human Experience

# Internet of Things Enhanced User Experience for Smart Water and Energy Management

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Smart environments can engage a wide range of end users with different interests and priorities, from corporate managers looking to improve the performance of their business to school children who want to explore and learn more about the world around them. Creating an effective user experience within a smart environment (from smart buildings to smart cities) is an important factor to success. In this article, we reflect on our experience of developing Internet-of-Things-enabled applications within a smart home, school, office building, university, and airport, where the goal has been to engage a wide range of users (from building managers to business travellers) to increase water and energy awareness, management, and conservation.

Driven by the idea of using ICT to more effectively and efficiently manage resources, smart environments have emerged in the form of smart cities, smart buildings, smart grids, smart water, and smart mobility.[1] Mark Weiser and colleagues define a smart environment as “a physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, embedded seamlessly in the everyday objects of our lives, and connected through a continuous network.”[2] A key driver in the development of smart environments is the convergence of technologies such as the Internet of Things (IoT) and big data, which are driving the

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digitization of physical infrastructures with sensors, networks, and social capabilities.[3] Smart environments, leveraging IoT, can support the development of resource management (for example, water/energy) applications for efficient and effective use of the resource within the environment.[4]

## IOT-ENABLED USER-EXPERIENCE FOR SMART WATER AND ENERGY MANAGEMENT

Building effective IoT applications for smart environments requires the combination of technology, techniques, and skills from multiple disciplines, from electronic engineering, data engineering, and data science, to user experience design and behavioral science. A key challenge in delivering smart environments is creating an effective user experience with new digital infrastructures.

We view this challenge within the Physical-Cyber-Social (PCS) computing paradigm[3] that supports a richer human experience with a holistic data-rich view of smart environments that integrate, correlate, interpret, and provide contextually relevant abstractions to humans. Figure 1 illustrates a model to structure the challenges based on our experiences of building IoT-enhanced applications for smart environments. The model is broken down into two parts, one with a focus on digitization of the environment using IoT and big data, and the other on Human Computing Interaction (HCI), behavioral models, and user experience design.

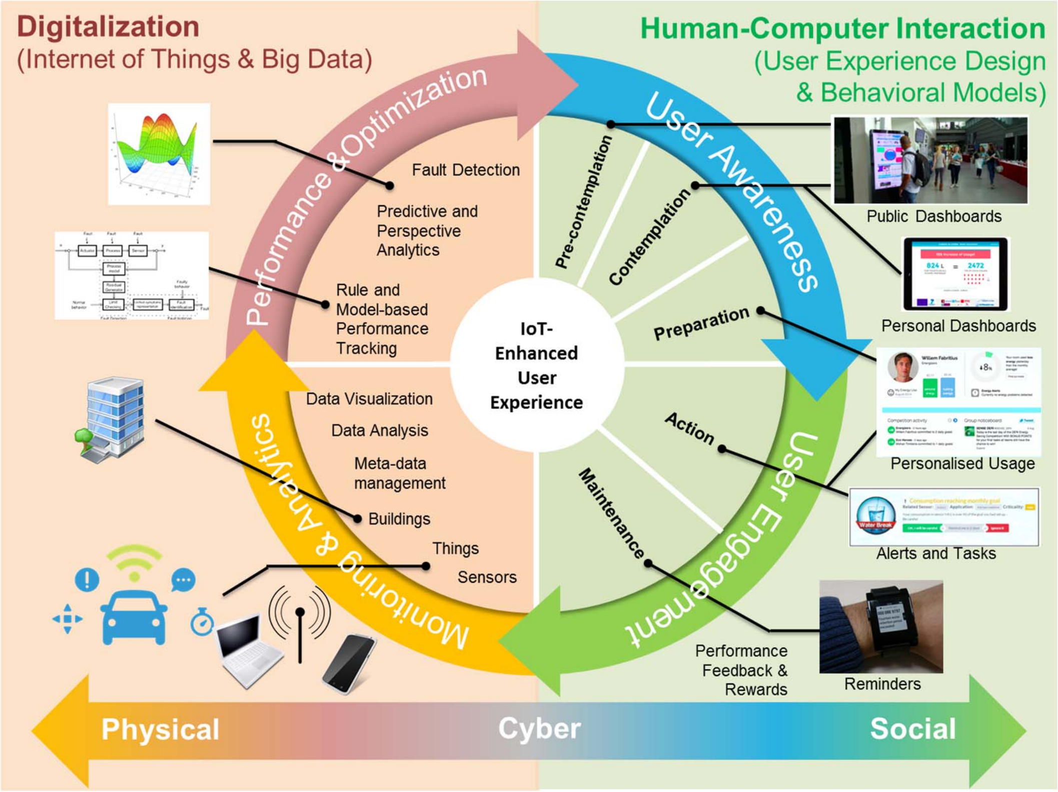


Figure 1. A model for IoT-enhanced user experience.

## Digitization: IoT and Big Data

The digitization of physical infrastructure (left side of Figure 1) may generate significant quantities of data on the usage of resources within a smart environment. In order to manage these resources holistically, it is important to follow a systematic approach to data gathering and analysis. The first phase in the model focuses on *monitoring and analysis* using IoT platforms and big data processing infrastructure to collect and analyze the data from the smart environment. This data can then be used within advanced decision support tools (that is, predictive and perspective analytics, simulations, and so on) to enhance the *performance and optimization* of resources within the smart environment (that is, reduced energy or water usage).[5]

## HCI: IoT-Enhanced User Experience and Behavioral Models

The human computing interaction phases of the model (right side of Figure 1) is where we look at how the insights generated from the IoT and big data analysis can be used to provide a seamless, personalized IoT-enhanced user experience, providing the right data to the right users at the right time. A key aspect of reducing water and energy usage is increasing users' awareness of their resource usage and changing their consumption behavior.

The activities in this part of the model increase *user awareness* through the use of targeted information delivery via personalized usage dashboards and task-oriented applications. Users are presented with meaningful and contextual information about usage, price, and availability in an intuitive and interactive way. Different users have different data requirements to manage their water or energy, from home users managing their personal usage, business users managing the consumption of their commercial activities, to municipalities managing regional distribution and consumption at the city level.

*User engagement* with the smart environment is critical to successful resource management by delivering actionable information to reduce consumption through the use of decision support tools. Engaging users is effective via proactive techniques including alerts, notifications, or requests for users to take physical actions in the environment.

When developing IoT-enhanced apps, it is important to consider well-established guidelines for the design of the applications. In the context of water and energy management, studying the design of conservation interventions in the workplace, user preferences for information visualizations, and the psychology of persuasion and motivation (among others) was necessary. As a result of this analysis, the core of the HCI side of the model leverages behavior change theories. The central assumption behind attitudinal theories of behavior change is that by influencing a person's attitude positively toward a behavior, they will subsequently act it out.

## The Transtheoretical Model: A User's Journey to Sustainability

The 40-year history of environmental psychology research has provided a wealth of theoretical models and best practices for influencing sustainable behavior. What remains a strong challenge for designers in the HCI community, however, is the translation of these theories into useful and engaging experiences that have the potential to influence behavior in a meaningful and long-lasting way. Many eco-feedback designs researched within the HCI community have lacked a theoretical connection to established psychological theory (from a recent review, it was less than half of papers surveyed[6]).

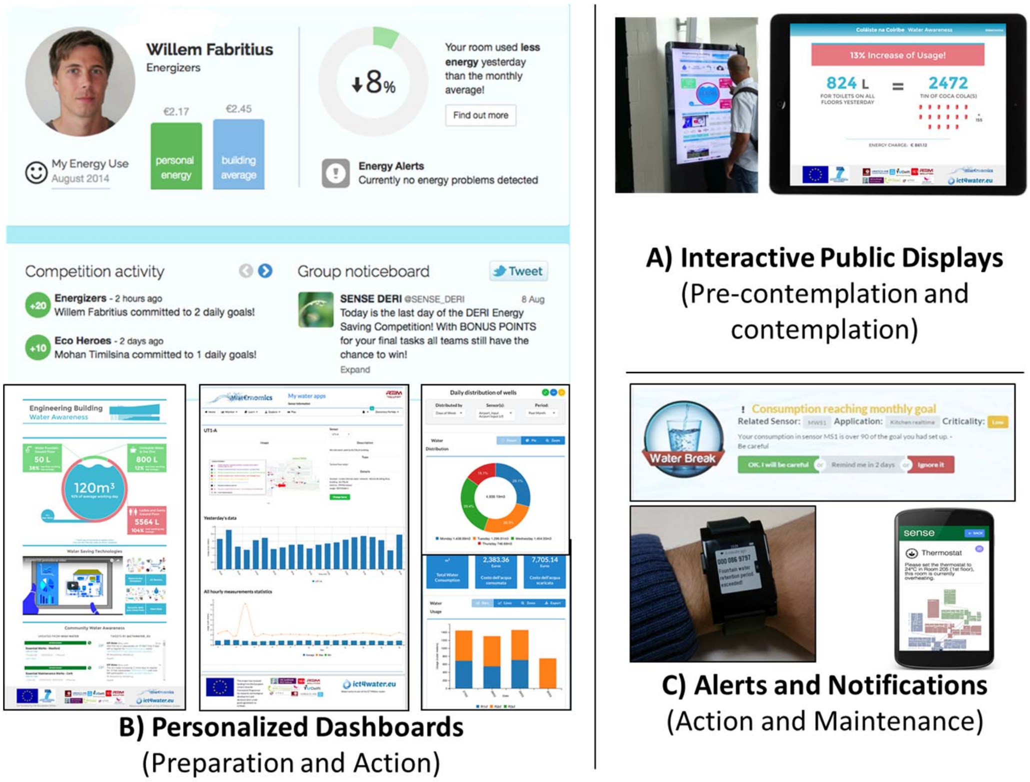
As a framework with which to bridge these multiple strands of behavior change theory, the Trans-Theoretical Model (TTM) can be used as a guiding heuristic for high-level user experience design. Developed by Prochaska and DiClemente,[7] the TTM model describes the "stages of change" a person goes through when modifying their behavior. The model has been developed and applied primarily within the field of healthcare, for example, in exercise and addiction treatment. Recently, the TTM model has been researched as a framework for energy feedback technology design (He and colleagues[8]). The TTM model can be used to help identify a user's information needs and appropriate persuasion strategies at each stage of change (see processes of change[7]), acting as a guiding design heuristic. Table 1 details the five stages of the TTM together with suggested interventions (He and colleagues[8]).

Table 1. Stages of behavior change in the transtheoretical model aligned with interventions.*

| TTM Stage | User Journey | User-Centric Intervention |
|---|---|---|
| Pre-contemplation | User is unaware of the problem | Create awareness about the issue. Highlight social norms and the benefits of changing behavior. Ensure a balanced argument and limited detail. (Apps: Public dashboard, newsletters) |
| Contemplation | User is aware of the problem and the desired behavior change | Make the case for using the system. Appeal to values, use persuasion strategies such as loss aversion, cognitive dissonance, and foot-in-the-door technique. (Apps: Personal dashboards) |
| Preparation | User intends to take action | Help users plan for change. Implement persuasion strategies such as goal setting and commitment. Provide support through mentoring. (Apps: Personalized dashboards, Tour, Goals) |
| Action | User practices the desired behavior | Provide timely feedback and positive reinforcement for targeted actions. Encourage intrinsic motivation through personalization. (Apps: Personalized dashboards, Alerts, Tasks, Guides, Rewards) |
| Maintenance | User works to sustain the behavior change | Help users form new habits. Use reminders and feedback toward goals. Encourage mentoring of others, journal keeping. Relapse between stages can happen at any time. (Apps: User activity, Rankings, Performance feedback and reminders) |

* The five stages of the transtheoretical model are used to define a user journey for smart energy and water environments.

To see an example of the TTM in action within an application refer to Figure 2B, which compares the user's energy consumption to that of his colleagues, utilizing the Social Proof strategy outlined by Cialdini.[9] The financial cost of the user's personal energy consumption is contrasted with that of the average person in the building. Costs are aggregated over a calendar month, allowing users to track their progress while also having a normative influence (social proof[9]). Other indicators invoke social norms that are both descriptive (showing monetary values) and injunctive (showing moral judgment through facial expressions).[9] The prominence and proximity of the user's name "Willem Fabritius" and photo aim to highlight that the energy consumption recorded is a personal reflection of themselves within their organization, triggering cognitive dissonance[10] when their personal image of being environmentally conscious does not match with the message portrayed. In addition, the prominence of the team name "Energizers" appeals to the user's sense of relatedness, a strategy for establishing intrinsic motivation.[7]



A) Interactive Public Displays (Pre-contemplation and contemplation)

B) Personalized Dashboards (Preparation and Action)

C) Alerts and Notifications (Action and Maintenance)

Figure 2. Smart applications targeting different parts of the user experience and stages of the transtheoretical model.

It should be noted that other models of behavior change could also be considered, including the Behavior Change Model (BCM) for sustainability by Geller.[11] The TTM model was preferred due to its perspective from the user's personal experience, which was useful in considering the user journey. The BCM can be described as being more focused on user behaviors and needs, and is specific to the sustainability context. Within our pilots we had a number of applications focused on social influence and gamification strategies, and the TTM model was seen as being more flexible when guiding design decisions outside of those focused on sustainability.

## PILOT STUDIES

In the past three years, based on the model in Figure 1, we have delivered a number of IoT-enabled smart water and energy management systems at a number of pilot sites. Across these pilot sites, there is a wide variety of end users (see Figure 3) from corporate managers looking to improve the performance of their operations to school children who could learn more about sustainability and their effects on the environment. The five pilot sites were:

- **Smart Airport:** Linate Airport in Milan represents a large-scale commercial scenario with a variety of water and energy consumers. The airport has been fitted with IoT-enabled infrastructure to manage its water and energy usage. The applications at Linate target both corporate and public users through interactive dashboards with water and energy saving opportunities.
- **Smart Homes:** The Municipality of Thermi in Greece provides a representative sample of domestic residences with varying profiles. Each of the residences has been enhanced with detailed metering of different water and energy consuming devices. The target audience are the resident adults and children. Other interested users include the municipality management and the utility operators.

- **Smart Buildings:** Two smart buildings at NUI Galway include the Insight Building and the Alice Perry Engineering Building, which is a state-of-the-art building with scores of sensors and actuators for the management of the building's water and energy consumption. Applications target staff members, managers, technicians, researchers, and students.
- **Smart School:** A newly constructed suburban school accommodating students aged 12 to 18 years old, together with teaching and operational staff. The building is equipped with a range of modern sensors. The applications are designed to appeal to students of the school, the building manager, and the general public (mainly parents).

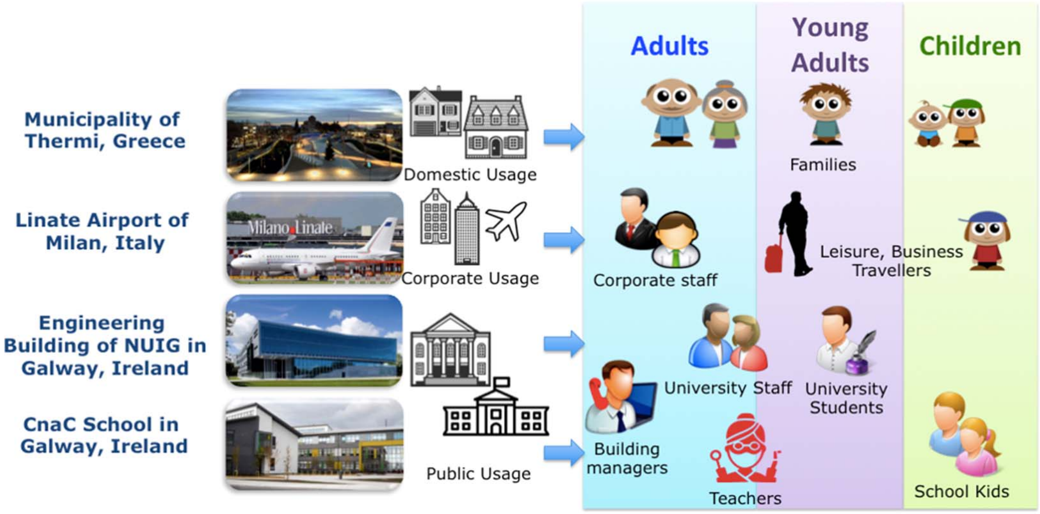


Figure 3. Target end user groups across different pilot sites.

## Methodology

The results and insights presented in the following sections are based on our experience in projects aimed at supporting energy and water management. In general, the projects followed a similar methodology for design, deployment, and evaluation of the system.[12] The high-level research methodology followed during the evaluation of the deployed systems is summarized in Table 2. Further details are available at www.waternomics.eu. During the initial period of the pilots, metering data was collected from existing systems to establish baselines across all pilots. During the control period, the users within the pilots had access to the data generated by the metering infrastructure system though traditional information systems (that is, building management system and basic public dashboards within the airports, office building, and school). The data collection period for each pilot spanned between 6 to 16 months, which also included a range of user interventions such as pre-surveys, focus groups, interviews, feedback cycles, and so on. The user experience evaluation included usability testing, usability field study, and user trials.

Table 2. Research methodology and impact for pilot sites.

| **Pilot Site** | **Users** | **Study Period** | **Baseline** | **Method** | **Actual Savings measured** | **Est. Annual Savings** | **User Awareness** |
|---|---|---|---|---|---|---|---|
| Linate Airport, Italy | Corporate Users<br>Passengers | 10 Mts | Pre-study water and energy usage | Passenger Survey<br>User trials<br>Staff questionnaires | 2,954 cubic meters<br>3,013 kg CO2 | 54,000 cubic meters<br>55,080 kg CO2 | Increases awareness of the problem.<br>Increase of responsibility and Personal norms |
| Thermi, Greece | Domestic Users<br>Utility Providers | 16 Mts | Manually recorded monthly water usage | Preliminary questionnaires (8 participants)<br>Focus groups Interviews | 30% water use reduction | -- | Increased awareness |
| National University of Ireland Galway, Ireland | University Students<br>Staff & Mgmt.<br>Public | 16 Mts | Pre-study water and energy usage | Pre-intervention survey (110 participants)<br>User trials and feedback cycles<br>Post-intervention survey (110 participants) | 174 cubic meters<br>177 kg CO2 | 8,089 cubic meters<br>8,251 kg CO2 | Limited increase (high existing awareness baseline) |
| Coláiste na Coiribe, Galway, Ireland | School Students<br>Staff & Mgmt.<br>Public | 12 Mts | Pre-study water and energy usage | Awareness questionnaire (150 participants)<br>User trials and feedback cycles<br>Post-intervention survey (70 participants) | 2,179 cubic meters<br>2,223 kg CO2 | 9,306 cubic meters<br>9,492 kg CO2 | Increased awareness in teachers<br>Increased awareness in junior students<br>Limited increase in senior students (high existing awareness baseline) |
| Insight, Ireland | 150 Office workers | 6 Mts | Average energy usage | User study (11 participants)<br>Field study (6 participants)<br>User trials (4-6 participants) | 23.86% energy use reduction | -- | Increased awareness on usage |

## INSIGHTS ON IOT-ENHANCED USER EXPERIENCE

Across the five pilot sites, we developed 25 different applications to support users to optimize resource usage from highly technical leakage detection apps for building managers to personal dashboards for office workers and children at home and at school. The process started with design examples of conservation systems within the HCI literature[6] and commercial sector. User experience tests helped improve the final designs and revealed a high level of communication of the apps. Based on a reflection of our experience across the pilot sites, the following lessons were identified as key learnings. They can be used to inform the user experience design of future applications for smart environments.

## Minimize Cognitive Overload with Clear and Focused Applications and Visualizations

Within the pilots, it was shown that participants had a preference for applications and visualizations that had a low cognitive load. Complex applications with full functionality were difficult for users to learn and understand. Users wanted simple (often single-purpose) applications over more elaborate multi-purpose ones. We recommend that visualizations and applications be tested early and often to ensure they are easily understood (matching the target users mental model), and serving the information needs and goals of the target users.[9,13] Strategies that can be employed to achieve easier cognition include providing a simplified core message with the ability for users to dig deeper on demand (progressive disclosure[9]), and harnessing the user's prior experience with design conventions (consistency[9]) and conceptual knowledge (priming[9]).

## Understand Your Users' Needs and Their Journey

When designing applications, consider each user and their stage in the journey. Customizing the apps to support a specific task or action helped to capture their interest and increase engagement. Within our pilots, we delivered 100 "personalized" versions of the 25 different apps to meet the specific needs of users. For example, building managers operate daily in the "Action" phase of the TTM and are interested in apps with concise messages that help them take immediate actions. Technicians were more interested in task-oriented apps with detailed consumption charts for a dedicated analysis and identification of potential issues in the system (Figure 2C). At the other extreme, airport passengers, parents, and kids at the "(pre-) contemplation" phase with a more casual interest wanted apps to help them explore the smart environment to learn more about it (see Figure 2A).

## Social Influence and Interaction Are Strong Motivators

Social influence was shown to be a strong motivator, which is consistent with observations found in the environmental psychology literature, particularly in the workplace.[14] The use of gamification with leaderboards and social benchmarking was effective in the pilots with users enjoying a friendly rivalry and social interaction with peers. However, the key question remains: Can this strategy maintain user interest in the long term? One answer may lie in the theory of intrinsic motivation, in which behaviors are performed for their inherent pleasure and are therefore more durable.[9]

## Close the Feedback Loop with Personalization

Within the pilots, users had a strong desire to have responsive feedback regarding the impact of their energy and water saving actions, allowing them to track their progress in a closed feedback loop.[9] This strategy appeals to the user's desire for control or mastery, increasing their intrinsic motivation.[15] This feedback was shown to be of most interest when presented as "people-centric," reporting on the participant's personal performance (including comparison to others) and the performance of teams in a competition.

## Bring Your "Humans in the Loop" of the Smart Environment

It is normal to view the user in the role of a consumer of water or energy whose behavior we want to change to reduce water and energy usage. However, users can actively engage in the system's operation by supporting it through citizen sensing[16] and citizen actuation.[17] Within our pilots, active participation of users in these roles improved their engagement and sense of ownership. In a citizen sensor role, the user can support data gathering in the environment by reporting observations (that is, water leaks, an empty room with lights turned on, a window open in a room with AC on). In the citizen actuator role, the user is asked by the IoT platform to take an action in the physical world, such as closing a window or turning off lights, for the purpose of energy saving. Although some tasks might get users' attention due to their altruistic nature, proper incentives (for example, leaderboards, badges, rewards) need to be designed and implemented for sustained participation of users over time.

## Careful Use of Targeted Alerts and Notifications

Information in IoT-enabled systems can overwhelm users. To minimize the search friction between actionable information and users, a well-designed notification system is needed. Emerging technologies and practices in user experience show that notifications will probably play a much more significant role in IoT-enabled systems.[18] Within the pilots, we aimed to enable notification to attract users' attention only when necessary. Furthermore, the notifications had to deliver actionable information to users. For example, building managers wanted alerts on faults and optimization opportunities. They had little interest in exploring charts of usage data, often commenting they do not have time to analyze data to gain any insights. In the pilot evaluations, it was found that the frequency of fault alert notifications must be carefully considered. Overwhelming recipients with notifications of potential faults was found to be counterproductive, leading to a potential disregarding of alert messages.

## SIDEBAR: REAL-TIME LINKED DATASPACES—A COMMON INFORMATION PLATFORM

Within each of the pilots, data management was provided by a Real-time Linked Dataspace (RLD) that combines the "pay-as-you-go" paradigm of dataspaces and linked data with entity-centric, real-time query capabilities. The RLD contains all the relevant information sources within a smart environment including things, sensors, and datasets and is responsible for managing the relationships between these participants. The RLD goes beyond a traditional dataspace approach[19] by supporting the management of entities within the smart environment as first-class citizens along with data sources, and it extends the dataspace support platform with unified queries across live streams, historical data, and entities. Figure 4 illustrates the architecture of the RLD with the following main concepts:

- **Things/Sensors:** Produce real-time data streams that need to be processed and managed. Things in a smart environment include connected devices, energy and water sensors, occupant sensors, and so forth**.**
- **Datasets**: Available in a wide variety of formats and accessible through different system interfaces. Example datasets include building management systems, energy and water management systems, passenger information systems, financial data, weather, (linked) open datasets, and so forth.
- **Entities:** Actively managed entities within the smart environment including their relationship to participating things, data sources, and other entities in the RLD.
- **Support Platform**: Responsible for providing the functionalities and services essential for managing the dataspace.
- **Apps, Analytics, and Users:** Interact with the RLD and leverage its data and services to provide data analytics, decision support tools, user interfaces, and data visualizations. Apps/Users can query the RLD in an entity-centric manner.

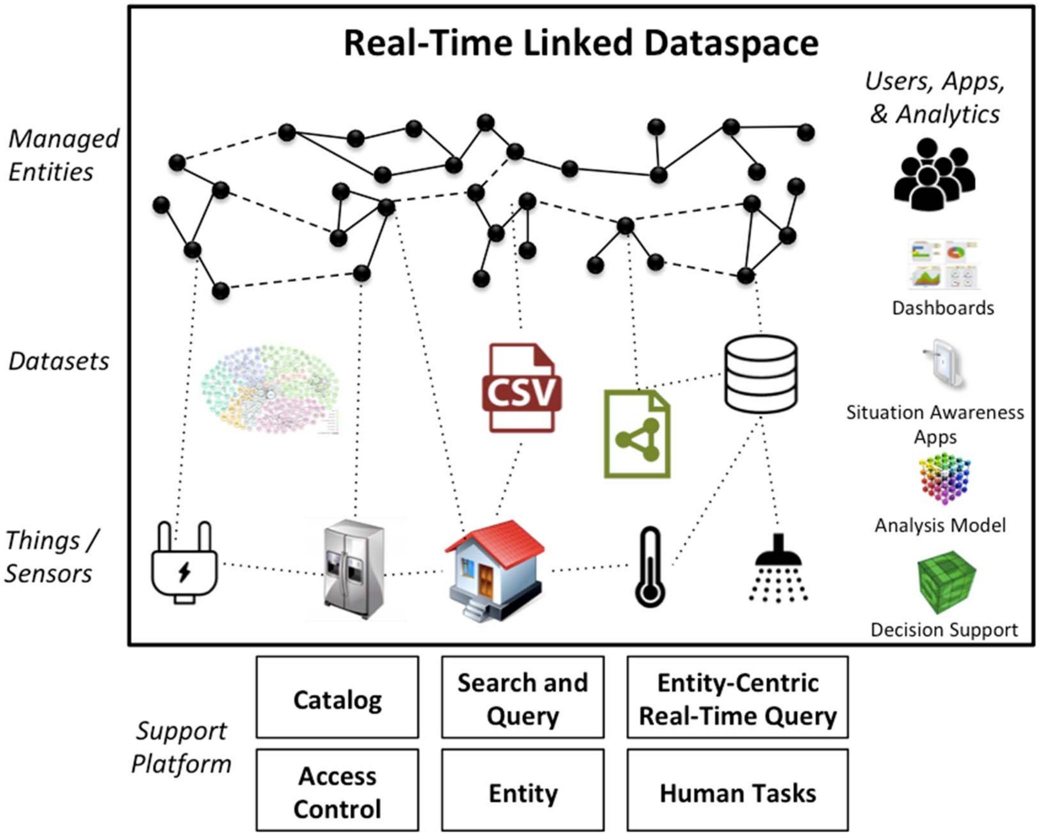


Figure 4. Architecture of the real-time linked dataspace.

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