Real-time Integration of Building Energy Data

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Thesis to obtain the Master of Science Degree in
Information Systems and Computer Engineering

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Agenda

- Introduction
- State of the art
- Motivation
- Problem Statement
- Proposed Solution
- Evaluation
- Conclusion
- Bibliography

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Three ways to improve **Energy Efficiency** in Buildings

[Pérez-Lombard et al., 2008]

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Energy Conservation

MIT Field Intelligence Laboratory

Introduction

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Schneider StruxureWare
Energy Dashboard

Introduction

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Intelligent Energy Management through an Energy Management System (EMS)

Introduction

An **EMS** track energy consumption in buildings to identify *problems* and *misuse situations*

Introduction

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Effective
Problem Solving

Early Problem
Detection (small ΔT)

Introduction

An **EMS** track energy consumption in buildings to identify *problems* and *misuse situations*

*Data must be collected continuously
and processed in (near) Real-Time*

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EMSs State of the art

1. Ubiquitous **Sensor Networks**
 - The raise of the “**Internet of Things**” (IoT)
2. **Large sets** of pervasive **Sensor Data**
 - Leads to the challenges of **Big Data**

EMSs State of the art

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2. **Large sets** of pervasive **Sensor Data**
 - Leads to the challenges of **Big Data**
3. DBMSs are not capable of processing such sensor data in Real-Time [Golab and Özsu, 2003]
 - **Big Data** is imposing a **paradigm shift** on how data is being processed

EMSs State of the art

1. Ubiquitous **Sensor Networks**
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3. DBMSs are not capable of processing such sensor data in Real-Time [Golab and Özsu, 2003]
 - **Big Data** is imposing a **paradigm shift** on how data is being processed
4. **EMSs are supported by DBMSs** [Kazmi et al., 2014]
 - EMSs are not prepared to process sensor data in real-time [Anjos et al. 2014]

EMSs State of the art

An EMS responding in **Real-Time** must be capable of process energy metering data within a **deadline of 5 minutes** [Granderson et al.,2011]

EMS	Data Processing Infrastructure	Real-Time Monitoring
EEMSuite ¹	DBMS	Hourly
EnergyWitness ²	DBMS	Quarter Hour
EnerwiseEM ³	DBMS	Hourly
OEIS ⁴	DBMS	Hourly

1 - "Enterprise Energy Management Suite"

(McKinstry)

2 - "EnergyWitness"

(Interval Data Systems, Inc.)

3 - "Enerwise Energy Manager"

(Enerwise Global Tech.)

4 - "Open Energy Information System"

(Lawrence Berkeley National Lab.)

EMSs State of the art

- EMSs rely on DBMSs to process **energy metering data streams**
- The **latency** of the **persistence step** is not compatible with the requirement of processing data in real-time

State of the art

There is some monitoring applications capable of real-time data processing, supporting a real-time decision making process

Real-Time Monitoring Applications	
Application Domain	Authors
Stock Market Transactions	(Chandramouli et al., 2010) (Mukherjee et al., 2010)
Healthcare Monitoring	(Jiang et al., 2011) (Zhang et al., 2010)
Network Traffic	(Akhtar and Siddiqui, 2011)
Weather Monitoring	(Li et al., 2008)

State of the art

We survey the architecture of these applications to conclude that they are supported by a **DSMS** (instead of by a DBMS)

Conclusions:

1. The **generic architecture** of an **EMS** is supported by traditional **DBMSs** (preventing RT data processing)
2. Sensor Network Monitoring Applications supported by **DSMSs** are **capable of RT data processing**

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- Q1 : Outliers.** *Identify the energy meters reporting an energy consumption 10% above the respective average over the last 8 hrs.*
- Q2 : Fault Detection.** *Identify faulty meters that are not being able of produce energy consumption measurements every 60 ± 5 secs.*
- Q3 : Variation.** *For each meter, determine the variation (%) of energy consumption from the average over the last 5 mins.*
- Q4 : Forecast.** *For each meter, give me its current and expected energy consumption. Being the expected value of each meter given by the AVG consumption of the current hour, computed along last month.*

Motivation

Evaluating Query Q1

Q1 : *“Identify the energy meters reporting an energy consumption 10% above the respective average over the last 8 hours.”*

Energy Consumption Sensor Data
Q1 Illustrative Evaluation

Motivation

Evaluating Query Q1

Q1 : “Identify the energy meters reporting an energy consumption 10% above the respective average over the **last 8 hours**.”

Energy Consumption Sensor Data
Q1 Illustrative Evaluation

Motivation

Evaluating Query Q1

Q1 : “Identify the energy meters reporting an energy consumption 10% above the *respective average* over the *last 8 hours*.”

Energy Consumption Sensor Data
Q1 Illustrative Evaluation

Motivation

Evaluating Query Q1

Q1 : “Identify the energy meters reporting an energy consumption 10% above the respective average over the last 8 hours.”

Energy Consumption Sensor Data
Q1 Illustrative Evaluation

Evaluation Requirements of Query Q1:

- I. Query must be **Evaluated Continuously**
(the last-8h-from-now interval is changing continuously)

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in order to be possible to timely process new data
as fast as it arrives—i.e. in **Real-Time**

Evaluation Requirements of Query Q1:

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- II. **Low Query Evaluation Latency**,
in order to be possible to timely process new data
as fast as it arrives—i.e. in **Real-Time**
- III. Compute **Data Aggregates** over **Moving Windows**
(e.g. the AVG operator over the 8-hour sliding time window)

Suitability of each Query Engine to evaluate Query Q1:

	Requirements	DBMS	DSMS
i.	Queries Evaluated Continuously	One-Time Queries	Continuous Queries
ii.	Low Query Evaluation Latency	Disk Access Overhead	In-memory Processing
iii.	Data Aggregates over Moving Windows	Lacks Windowing Ops.	Built-in Windowing Ops.

Suitability of each Query Engine to evaluate Query Q1:

Conclusion

DBMSs are not the best solution to support a Real-Time Monitoring EMS

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Problem Statement

This dissertation aims to validate the **thesis** that:

“An EMS supported by a DSMS outperforms an EMS supported by a DBMS, on processing energy metering data in real-time.”

Better Performance		i. Lower Query Evaluation Latency ii. Greater Query Language Expressibility
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Proposed Solution

Proposed Data Processing Architecture

Generic **Architecture of an EMS** is organized in **3 Tiers**

Proposed Solution

Proposed Data Processing Architecture

Proposed Solution

Proposed Data Processing Architecture

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Proposed Data Processing Architecture

Proposed Solution

Proposed Data Processing Architecture

Proposed Architecture main feature:

- **Pipeline of data transformations supported by a DSMS**

Proposed Solution

Proposed Data Processing Architecture

Adapters. Mediate the **extraction** of data from several sources into the data transformation process.

Proposed Solution

Proposed Data Processing Architecture

Data Integration. Data cleaning and integration steps used to compute a set of data streams tightly related with the problem domain.

Proposed Solution

Proposed Data Processing Architecture

Data Evaluation. Supports the evaluation of **energy management queries**, those representing the energy monitoring use-case scenarios.

Proposed Solution

Requirements Analysis

Literature Survey to identify the type of **Data Transformations** (case study) that must be performed by the proposed **Data Processing Arch.**

Surveyed Authors

- Akhtar and Siddiqui, 2011
- Babcock et al., 2002
- Bizer et al., 2009
- Bonnet et al., 2001
- Chandramouli et al., 2010
- Cranor et al., 2003
- Madden and Franklin, 2002
- Mukherjee et al., 2010
- Zhang et al., 2010

Surveyed Authors

- Granderson et al., 2011

Proposed Solution

Requirements Analysis

Case Study: 16 queries covering the surveyed application domains

Q#	Continuous Query Statement	Class of Queries				Technique	
		Detection of Abnormal Values	Data Stream Instant Summary Metrics	Data Stream Metadata Evaluation	Database Integration	Load Profiling	Peak Load Analysis
Use Case Scenarios							
1	Identify the energy meters for which the reported energy consumption variation, along the last 5 minutes, has increased more than 20%.	●	○	○	○	●	○
2	Identify the energy meters producing measurements with a periodicity out of 60+-5 range of seconds.	●	○	○	○	—	—
3 [†]	Identify the energy meters that are reporting energy consumption measurements 20% above than the respective average of last 24 hours.	●	○	○	○	○	●
4	For each energy meter, computes the fraction of its reported measurements relative to the total of energy that is being consumed by the building.	○	●	○	○	●	○
5	Sort in decreasing order the energy meters by its current energy consumption measurements.	○	●	○	○	●	○
6 [†]	For each energy meter and building as a whole, compute the Minimum/Maximum energy consumption ratio along last hour.	○	●	○	○	○	●
7	Identify the energy meters that are reporting measurements above a respective threshold.	●	○	○	○	○	●
8 [†]	(...)						
Integration Queries to support Use Case Scenarios							
10	For each data stream, aggregate its three-phase current measurements into the total amount of energy being consumed, and then adorn the result stream with the location properties of the respective energy meter, which is available through a database of metadata.	○	●	○	●	—	—
11 [†]	For each data stream, compute the variation of its current measurement value from the moving average of last 5 minutes.	○	●	○	○	●	○
12 [†]	For each data stream, compute the period between its two last measurements.	○	○	●	○	—	—
13 [†]	(...)						

Proposed Solution

Requirements Analysis

Case Study: 9 Scenarios on monitoring building energy consumption, composed by a **graph (pipeline) of 16 Queries**

Proposed Solution

Requirements Analysis

Scenario 3: “Identify the energy meters reporting an energy consumption (Motivation Q1) 20% above the respective average over the last 24 hours.”

Proposed Solution

Case Study — Building Energy Metering Network

- Energy metering network of **8 meters**
- **8 locations** being continuously monitored ($\approx$ total **1365 m²**)
(Four types of places: **Offices**, **Library**, **Lecture Halls**, and **Class Rooms**)
- **Real Environment**, Real Dataset
- **3-Phase Current** power supplying the building

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Evaluation

Methodology

- Implementation of **two prototypes** of the proposed Data Processing Architecture:
 - DSMS supported
(our proposed approach)
 - DBMS supported
(state-of-the-art approach)

Two orthogonal implementations of
Proposed Data Processing Architecture
Benchmark Evaluation

Evaluation

Methodology

- Implementation of **two prototypes** of the proposed Data Processing Architecture:
 - DSMS supported**
(our proposed approach)
 - DBMS supported**
(state-of-the-art approach)
- To perform a **Benchmark Evaluation** between the proposed solution and a state-of-the-art based solution

Two orthogonal implementations of
Proposed Data Processing Architecture
Benchmark Evaluation

Evaluation

Methodology

- **DSMS Solution**
supported by **ESPER**
 - i. An open-source DSMS that provides a **declarative SQL-like query language**
 - ii. Allowing a **side-by-side comparison with DBMS's SQL**

Two orthogonal implementations of
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Methodology

- **DSMS Solution**

supported by **ESPER**

- An open-source DSMS that provides a **declarative SQL-like query language**
- Allowing a **side-by-side comparison with DBMS's SQL**

- **DBMS Solution**

supported by **PostgreSQL**

- The most well-known and widely-used open-source DBMS

Two orthogonal implementations of
Proposed Data Processing Architecture
Benchmark Evaluation

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Methodology

- All **9 Scenarios** were implemented in both **DSMS** and **DBMS** solutions

Two orthogonal implementations of
Proposed Data Processing Architecture
Benchmark Evaluation

Evaluation

Methodology

- All **9 Scenarios** were implemented in both **DSMS** and **DBMS** solutions
- Evaluation Dimensions:
 1. **Query Language** Evaluation
 2. **Performance** Evaluation
- Assess the ability of **each solution** to express and timely evaluate the **9 Scenarios**

Two orthogonal implementations of
Proposed Data Processing Architecture
Benchmark Evaluation

Evaluation

Query Language Evaluation

Relative difficulty of implementing the **Use-Case Queries (Q1–Q16)** on both DSMS and DBMS based solution

Query #	Ease of Query Implementation					
	DSMS			DBMS		
	Easy	Hard	Very Hard	Easy	Hard	Very Hard
Evaluation						
1	●	○	○	●	○	○
2	●	○	○	●	○	○
3	●	○	○	○	○	●
7	●	○	○	○	○	○
8	●	○	○	○	●	○
9	●	○	○	●	○	○
Integration						
4	●	○	○	●	○	○
5	●	○	○	●	○	○
6	●	○	○	○	●	○
10	●	○	○	●	○	○
11	●	○	○	○	●	○
12	●	○	○	○	●	○
13	●	○	○	○	●	○
14	●	○	○	●	○	○
15	●	○	○	●	○	○
16	●	○	○	○	○	●

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3	●	○	○	○	○	●
7	●	○	○	○	○	○
8	●	○	○	○	●	○
9	●	○	○	●	○	○
Integration						
4	●	○	○	●	○	○
5	●	○	○	●	○	○
6	●	○	○	○	●	○
10	●	○	○	●	○	○
11	●	○	○	○	●	○
12	●	○	○	○	●	○
13	●	○	○	○	●	○
14	●	○	○	●	○	○
15	●	○	○	●	○	○
16	●	○	○	○	○	●

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7	●	○	○	○	○	○
8	●	○	○	○	●	○
9	●	○	○	●	○	○
Integration						
4	●	○	○	●	○	○
5	●	○	○	●	○	○
6	●	○	○	○	●	○
10	●	○	○	●	○	○
11	●	○	○	○	●	○
12	●	○	○	○	●	○
13	●	○	○	○	●	○
14	●	○	○	●	○	○
15	●	○	○	●	○	○
16	●	○	○	○	○	●

Evaluation

Query Language Evaluation

Relative difficulty of implementing the **Use-Case Queries (Q1–Q16)** on both DSMS and DBMS based solution

Query #	Ease of Query Implementation						Features Hindering Query Implementation in the DBMS	
	DSMS			DBMS			Windowing Query	Grouped/Agg. Query Projecting Not Grouped/Agg. Attributes
	Easy	Hard	Very Hard	Easy	Hard	Very Hard		
Evaluation								
1	●	○	○	●	○	○	○	○
2	●	○	○	●	○	○	○	○
3	●	○	○	○	○	●	●	●
7	●	○	○	○	○	○	○	○
8	●	○	○	○	●	○	●	○
9	●	○	○	●	○	○	○	○
Integration								
4	●	○	○	●	○	○	○	○
5	●	○	○	●	○	○	○	○
6	●	○	○	○	●	○	●	○
10	●	○	○	●	○	○	○	○
11	●	○	○	○	●	○	●	○
12	●	○	○	○	●	○	●	○
13	●	○	○	○	●	○	●	○
14	●	○	○	●	○	○	○	○
15	●	○	○	●	○	○	○	○
16	●	○	○	○	○	●	●	●

Issue 1. Implementing Windows.

- DSMS Solution → Built-in Window Ops. (Easy)
- DBMS Solution → *through Self-Join* (Hard)

Issue 2. Grouped/Aggregated Query Projecting Not Grouped/Aggregated Attributes.

Example: *“For each meter, return its current **measurement**,
TS, and the **AVG** of **measurements** received so far.”*

Evaluation

Query Language Evaluation

Issue 2. Grouped/Aggregated Query Projecting Not Grouped/Aggregated Attributes.

Example: “For each meter, return its current **measurement**,
TS, and the **AVG** of **measurements** received so far.”

Batch Evaluation Approach
DBMS One-Time Queries

```
SELECT Device, TS, Measure, AVG(Measure)
FROM InputDataStreamTable
GROUP BY Device
```

Device	TS	Measure	AVG(M.)
Lib.	8:10	103	109
	8:11	107	
	8:12	117	
A4	8:10	23	28
	8:11	29	
	8:12	32	

(Impossible) Resultset

2 Rows ✕ 3 Rows 2 Rows

Evaluation

Query Language Evaluation

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Example: “For each meter, return its current measurement, TS, and the AVG of measurements received so far.”

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(Impossible) Resultset

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A4	8:10	23	28
	8:11	29	
	8:12	32	

2 Rows ✕ 3 Rows 2 Rows

```
SELECT Device, TS, Measure, AVG(Measure) OVER W
FROM InputDataStreamTable
WINDOW W AS (PARTITION BY Device
ORDER BY TS ASC
RANGE BETWEEN CURRENT ROW
AND UNBOUNDED FOLLOWING)
```

(Valid) Snapshot

Device	TS	Measure	AVG(M.)
Lib.	8:10	103	103
Lib.	8:11	107	105
Lib.	8:12	117	109
A4	8:10	23	23
A4	8:11	29	26
A4	8:12	32	28

6 Rows 6 Rows 6 Rows

Issue 2. Grouped/Aggregated Query Projecting Not Grouped/Aggregated Attributes.

Example: “For each meter, return its current **measurement**,
TS, and the **AVG** of **measurements** received so far.”

Incremental Evaluation Approach
DSMS Continuous Queries

```
SELECT Device, TS, Measure, AVG(Measure)
FROM InputDataStream
GROUP BY Device
```

Evaluation

Query Language Evaluation

Practical Consequences of *Issue 1* and *Issue 2*

Use-Case Query Q16: *For each meter, give me its current and expected energy consumption. Being the expected value of each meter given by the AVG consumption of the current hour, computed along last month.*

```
1 CREATE MATERIALIZED VIEW "Q16_ExpectedLastMonthPivotHourAVG" AS
2 SELECT rel.device_pk AS device_pk,
3        rel.measure_timestamp_pivot AS measure_timestamp,
4        rel.measure AS current_measure,
5        rel.expecetd_measure AS expecetd_measure,
6        'WATT/m^2' AS measure_unit,
7        'Current and Expected Power consumption given by the
8         AVG of the current hour computed along last month' AS measure_description,
9        rel.device_location AS device_location,
10       rank() OVER w2 AS index
11 FROM (SELECT pivot_measures.device_pk AS device_pk,
12            pivot_measures.measure_timestamp AS measure_timestamp_pivot,
13            cluster_measures.measure_timestamp AS measure_timestamp_cluster,
14            pivot_measures.measure AS measure,
15            AVG(cluster_measures.measure) OVER w1 AS expecetd_measure,
16            pivot_measures.measure_description AS measure_description,
17            pivot_measures.measure_unit AS measure_unit,
18            pivot_measures.device_location AS device_location,
19            rank() OVER w1 AS rank
20 FROM "Q14_Normalization" cluster_measures
21 JOIN
22      "Q14_Normalization" pivot_measures
23 ON cluster_measures.device_pk = pivot_measures.device_pk
24 AND cluster_measures.measure_timestamp <= pivot_measures.measure_timestamp
25 AND cluster_measures.measure_timestamp > (pivot_measures.measure_timestamp - '1 month')
26 WINDOW w1 AS (PARTITION BY cluster_measures.device_pk,
27                        date_part('hour', cluster_measures.measure_timestamp),
28                        pivot_measures.index
29 ORDER BY cluster_measures.measure_timestamp
30 DESC RANGE BETWEEN CURRENT ROW AND UNBOUNDED FOLLOWING)
31 ) rel
32 WHERE rel.rank = 1
33 AND date_part('hour', rel.measure_timestamp_pivot) = date_part('hour', rel.measure_timestamp_cluster)
34 WINDOW w2 AS (PARTITION BY rel.device_pk
35 ORDER BY rel.measure_timestamp_pivot DESC)
```

Practical Consequences of *Issue 1* and *Issue 2*

Use-Case Query Q16: *For each meter, give me its current and expected energy consumption. Being the expected value of each meter given by the AVG consumption of the current hour, computed along last month.*

```
1 INSERT INTO Q16_ExpectedLastMonthPivotHourAVG
2 SELECT device_pk          AS device_pk,
3        measure_timestamp AS measure_timestamp,
4        measure           AS current_measure,
5        AVG(measure)      AS expected_measure,
6        "WATT/m^2"        AS measure_unit,
7        "Current and Expected Power consumption given by the
8         AVG of the current hour computed along last month" AS measure_description,
9        device_location   AS device_location
10 FROM Q14_Normalization.win:ext_timed(measure_timestamp, 1 month)
11 GROUP BY device_pk,
12         DateTime.toDate(measure_timestamp, "yyyy-MM-dd HH:mm:ss").getHours()
```

Q16 implementation in EPL (Esper)

Query Language Evaluation Results:

*DSMS's Query Language is most suitable
to write and evaluate queries
than SQL Query Language of DBMSs*

Evaluation

Performance Evaluation

Assess the ability of each solution to **process the arriving energy metering data streams in real-time.**

Methodology:

Evaluation

Performance Evaluation

Assess the ability of each solution to **process the arriving energy metering data streams in real-time.**

Methodology:

$$T_{Process(\epsilon)} = T_{Queue(\epsilon)} + T_{Scenario(\epsilon)} \leq \text{Real-Time Threshold} \quad (.5 mins.)$$

Experimental Setup:

- **9 Scenarios** Evaluated (*one at a time*)
- **18 Tests** as a Total (DBMS Sol. + DSMS Sol.)

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- **10-hour** duration for each test
- **8 energy meters**
- Each meter: **4 measurements/minute**
- Total of **19200 measurements** delivered along 10 hours
(**57600 tuples**, 3-Phase current)

Experimental Setup:

- **9 Scenarios** Evaluated (*one at a time*)
- **18 Tests** as a Total (DBMS Sol. + DSMS Sol.)
- **10-hour** duration for each test
- **8 energy meters**
- Each meter: **4 measurements/minute**
- Total of **19200 measurements** delivered along 10 hours
(**57600 tuples**, 3-Phase current)
- **1,875 secs.**, average arrival period of each measurement

Evaluation

Performance Evaluation – Scalability of Scenario Evaluation Latency

Results of the Experiments: $T_{Process(\epsilon)} = T_{Queue(\epsilon)} + T_{Scenario(\epsilon)}$

Scenario 3: “Identify the energy meters reporting an energy consumption (Motivation Q1) 20% above the respective average over the last 24 hours.”

Evaluation

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Scenario 3: “Identify the energy meters reporting an energy consumption (Motivation Q1) 20% above the respective average over the last 24 hours.”

Evaluation

Performance Evaluation – Evolution of Queue Waiting Time

Results of the Experiments: $T_{Process(\epsilon)} = T_{Queue(\epsilon)} + T_{Scenario(\epsilon)}$

Scenario 3: “Identify the energy meters reporting an energy consumption (Motivation Q1) 20% above the respective average over the last 24 hours.”

(a) Time a measurement had to wait in the queue to be processed
DBMS Solution

(b) Time a measurement had to wait in the queue to be processed
DSMS Solution

Evaluation

Performance Evaluation – Scalability of Evaluation Latency for all 9 Scenarios

Results of the Experiments: $T_{Process}(\epsilon) = T_{Queue}(\epsilon) + T_{Scenario}(\epsilon)$

Evaluation

Performance Evaluation – Evolution of Queue Waiting Time for all 9 Scenarios

Results of the Experiments: $T_{Process(\epsilon)} = T_{Queue(\epsilon)} + T_{Scenario(\epsilon)}$

Scenario 3: “Identify the energy meters reporting an energy consumption (Motivation Q1) 20% above the respective average over the last 24 hours.”

(a) Time a measurement had to wait in the queue to be processed
DBMS Solution

(b) Time a measurement had to wait in the queue to be processed
DSMS Solution

Performance Evaluation Results:

- **DBMS Solution** *failed* to timely evaluate energy metering data in **8 of 9 Scenarios**
- **DSMS Solution** *successfully* evaluated in RT the energy metering data in **all 9 Scenarios**

Performance Evaluation Results:

- **DBMS Solution** *failed* to timely evaluate energy metering data in **8 of 9 Scenarios**
- **DSMS Solution** *successfully* evaluated in RT the energy metering data in **all 9 Scenarios**

An EMS aiming at processing energy metering data in real-time must be supported by a DSMS, instead of by a DBMS

Agenda

- Introduction
- State of the art
- Motivation
- Problem Statement
- Proposed Solution
- Evaluation
- **Conclusion**
- Bibliography

Conclusion

- Current **EMSs are using a DBMSs** to process sensor data, preventing them to monitor energy metering networks in real-time.
- **DSMSs are used to process data streams efficiently** in several domains.
- We introduced an **EMS's Data Processing Architecture supported by a DSMS**.
- **Benchmark evaluation** show that our solution outperformed the state of the art approach in both **data evaluation latency** and **query language expressibility**
- We **validated our hypothesis** that, to process energy metering data streams in real-time, **EMSs should be supported by DSMSs, instead of DBMSs**.

Conclusion

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Paulo Carreira

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Conclusion

2nd Article Submitted to ICDE16

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Real-Time Monitoring of Building Energy Metering Networks

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Abstract—Energy Management Systems (EMSs) are used to monitor energy consumption in buildings with the purpose of improving energy efficiency, by identifying savings opportunities and misuse situations. To achieve that, an EMS collects energy metering data streams from a network of energy meters in the

required information to determine the adjustments towards improving energy usage [4].

One fundamental aspect of energy management is timeliness: faster decisions translate to less waste and larger savings.

Real-time Integration of Building Energy Data

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November 20, 2015

Bibliography (1 of 3)

D.Anjos, P.Carreira, and A.P.Francisco. **Real-time integration of building energy data**. In Big Data (BigData Congress), 2014 IEEE International Congress on, pages 250–257. IEEE, 2014.

N.Akhtar and F.H.Siddiqui. **UDP packet monitoring with stanford data stream manager**. In 2011 International Conference on Recent Trends in Information Technology (ICRTIT), pages 533–537. Ieee, June 2011.

B.Babcock, S.Babu, M.Datar, R.Motwani, and J.Widom. **Models and issues in data stream systems**. In Proceedings of the twenty-first ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems, pages 1–16. ACM, 2002

C.Bizer and A.Schultz. **The Berlin sparql benchmark**. 2009.

P.Bonnet, J.Gehrke, and P.Seshadri. **Towards sensor database systems**. In Mobile Data Management, pages 3–14. Springer, 2001.

C.Cranor, T.Johnson, and O.Spataschek. **Gigascop : A Stream Database for Network Applications**. In Proceedings of the 2003 ACM SIGMOD International Conference on Management of Data, pages 647–651. ACM, 2003. ISBN 158113634X.

Bibliography (2 of 3)

B.Chandramouli, M.Ali, J.Goldstein, B.Sezgin, and B.S.Raman. **Data stream management systems for computational finance.** Computer, (12):45–52, 2010

L.Golab and M.T.Özsu. **Issues in data stream management.** ACM Sigmod Record, 32(2):5–14, 2003.

J.Granderson, M.Piette, B.Rosenblum, and et al. L.Hu. **Energy Information Handbook: Applications for Energy-Efficient Building Operations.** Lawrence Berkeley National Laboratory, LBNL-5272E., 2011

X.Jiang, S.Yoo, and J.Choi. **Dsms in ubiquitous-healthcare: A borealis-based heart rate variability monitor.** In Biomedical Engineering and Informatics (BMEI), 2011 4th International Conference on, volume 4, pages 2144–2147. IEEE, 2011

A.H.Kazmi, M.J.O’grady, D.T.Delaney, A.G.Ruzzelli, and G.M.P.O’hare. **A review of wireless sensor-network-enabled building energy management systems.** ACM Trans. Sen. Netw., 10(4):66:1–66:43, 2014.

X.Li, B.Plale, N.Vijayakumar, R.Ramachandran, S.Graves, and H.Conover. **Real-time storm detection and weather forecast activation through data mining and events processing.** Earth Science Informatics, 1(2):49–57, 2008

Bibliography (3 of 3)

S.Madden and M.J.Franklin. Fjording the Stream : An Architecture for Queries over Streaming Sensor Data. In Data Engineering, 2002. Proceedings. 18th IEEE International Conference on, pages 555—566, 2002.

A.Mukherjee, P.Diwan, P.Bhattacharjee, D.Mukherjee, and P.Misra. **Capital market surveillance using stream processing**. In Computer Technology and Development (ICCTD), 2010 2nd International Conference on, pages 577–582. IEEE, 2010.

L.Pérez-Lombard, J.Ortiz, and C.Pout. **A review on buildings energy consumption information**. Energy and Buildings, 40(3):394–398, Jan. 2008.

Q.Zhang, C.Pang, S.Mcbride, D.Hansen, C.Cheung, and M.Steyn. **Towards health data stream analytics**. In Complex Medical Engineering (CME), 2010 IEEE/ICME International Conference on, pages 282–287. IEEE, 2010.

Backup Slides

Evaluation

Methodology

- All **9 Use-Case Scenarios** were implemented in both **DSMS** and **DBMS** solutions
- To feed these scenarios with energy metering data streams we implement a **Simulator** of Taguspark Energy Metering Nw.
 - I. Deterministic Datasets*
 - II. Configurable Time Ranges*
 - III. Configurable Load*

Yet, still a **real-world dataset**

Two orthogonal implementations of
Proposed Data Processing Architecture
Benchmark Evaluation

Problem Statement

- The **motivation** of this research work:
“EMSs must be capable of processing energy metering data in Real-Time, to improve energy efficiency in buildings.”
- The **problem** identified by this research work:
“By being supported by DBMSs, current EMSs are struggling to process energy metering data streams in real-time.”
- This dissertation aims to validate the **thesis** that:
“An EMS supported by a DSMS outperforms an EMS supported by a DBMS, on processing energy metering data in real-time.”

Better
Performance

- i. Lower Query **Evaluation Latency**
- ii. Greater Query **Language Expressibility**

Related Work

	Language Model																									
	Single Tuple				Logic						Windows					Flow Management										
Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deploynt Model	Open Source
Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes
COUGAR	●	●	●	●	—	—	—	—	—	—	○	○	●	○	○	●	●	—	●	—	○	●	—	s	D	Yes
CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C+	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

	Language Model																									
	Single Tuple				Logic						Windows					Flow Management										
Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deployment Model	Open Source
Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes
COUGAR	●	●	●	●	—	—	—	—	—	—	○	○	●	○	○	●	●	—	●	—	○	●	—	s	D	Yes
CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C+	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

Related Work

Data Stream

Event Stream

	Language Model																									
	Single Tuple				Logic						Windows					Flow Management										
Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deployent Model	Open Source
Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes
COUGAR	●	●	●	●	—	—	—	—	—	—	○	○	●	○	○	●	●	—	●	—	○	●	—	s	D	Yes
CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C+	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

Related Work

Data Stream

Event Stream

Data + Event Stream

	Language Model																									
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Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deploy ment Model	Open Source
Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes
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CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C+	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

Related Work

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Event Stream

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Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
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Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
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CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C†	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

Related Work

Data Stream

Event Stream

Data + Event Stream

	Language Model																										
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Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deployment Model	Open Source	
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NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes	
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes	
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes	
COUGAR	●	●	●	●	—	—	—	—	—	—	○	○	●	○	○	●	●	—	●	—	○	●	—	s	D	Yes	
CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes	
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes	
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes	
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C+	Yes	
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes	
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes	

Related Work

Data Stream

Event Stream

Data + Event Stream

	Language Model																									
	Single Tuple				Logic						Windows					Flow Management										
Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deployment Model	Open Source
Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes
COUGAR	●	●	●	●	—	—	—	—	—	—	○	○	●	○	○	●	●	—	●	—	○	●	—	s	D	Yes
CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C+	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

Related Work

	Language Model																									
	Single Tuple				Logic						Windows					Flow Management										
Systems	Selection	Projection	Renaming	Extended Projection	Conjunction	Disjunction	Repetition	Negation	Sequence	Iteration	Fixed	Landmark	Sliding	Tumble	User Defined	Join	Union	Except	Intersect	Remove Dup.	Duplicate	Group By	Order By	User-Defined Aggregates	Deployment Model	Open Source
Stream	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●	●	●	●	●	●	●	●	○	C	Yes
NiagaraCQ	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	●	—	●	○	○	●	○	●	C	Yes
Borealis	●	●	○	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	○	○	●	●	○	●	C	Yes
TelegraphCQ	●	●	●	—	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	—	D	Yes
COUGAR	●	●	●	●	—	—	—	—	—	—	○	○	●	○	○	●	●	—	●	—	○	●	—	s	D	Yes
CEDR	●	●	●	●	●	●	○	●	●	○	○	○	○	○	○	●	●	●	●	○	○	●	○	●	C	Yes
Cayuga	●	●	●	○	●	●	○	○	●	●	○	○	○	○	○	●	○	○	○	○	○	○	○	○	C	Yes
SASE/SASE+	●	○	○	●	●	●	○	●	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	C	Yes
ESPER	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●	●	●	○	○	○	○	●	●	●	C†	Yes
Twitter Storm	●	●	●	●	●	●	—	—	●	●	●	—	●	—	—	●	●	—	—	—	●	●	●	●	D	Yes
Apache S4	●	●	●	●	●	●	—	—	●	●	—	—	●	—	—	●	—	—	—	—	—	●	—	●	D	Yes

- ***Data Management Systems*** (DSMSs)
 - Properly designed to process huge amounts of data streams with the *lowest possible latency*
 - Store queries (instead of data), receive data (instead of queries)