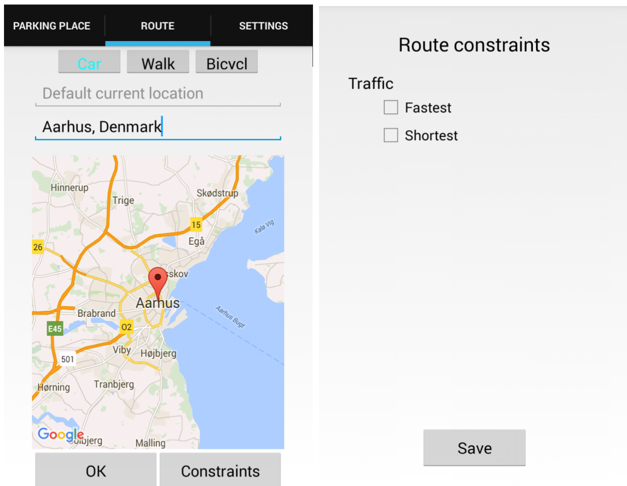
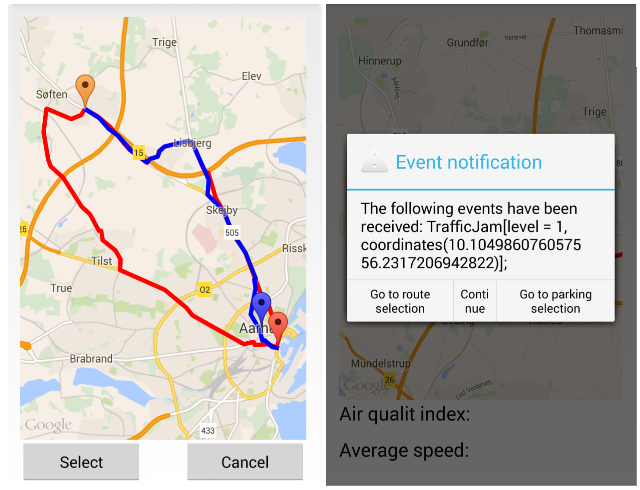


a) b)

Figure 18. The user interfaces of the Android application used to select the starting point (a) and the travel preferences (b).



a) b)

Figure 19. The user interfaces of the Android application: a) select the preferred route; b) notification of a traffic jam which appeared on the selected route while the user is travelling.

functional constraints. These preferences can be the minimization or the maximisation of travel time or distance.

The functional constraints and preferences specify different thresholds and minimisation criteria for electing the route. During the development of the mobile application the domain expert has computed a default set of values for these thresholds. As a result of that, the route constraints user interface from.

Figure 18 b) allows the user to select between the fastest/shortest routes. If needed, more fields can be added in this user interface in order to allow more fine-grained constraints specification, but the usability of the application may suffer.

```
1.  input_get_routes(SP, EP, V, 5) :-
     parameter("STARTING_POINT", SP),
     parameter("ENDING_POINT", EP), route_costMode(V).
2.  route(@get_routes(SP, EP, V, N)) :- input_get_routes(SP, EP, V, N).
3.  route_data(@get_routes_data(SP, EP, V, N)) :- input_get_routes(SP,
    EP, V, N).
4.  parameter("STARTING_POINT","10.116919 56.226144").
5.  parameter("ENDING_POINT","10.1591864 56.1481156").
6.  minimize{AV@2 : valueOf("DISTANCE", AV)}.
7.  minimize{AV@1 : valueOf("TRAVEL_TIME ", AV)}.
```

Listing 5. A snapshot of logic decision support rules for the Travel Planner scenario.

This concrete reasoning request is automatically mapped into ASP rules (see example rules 4-7 in Listing 5), and combined with the specific scenario-driven rules for the Travel Planner Decision Support module.[16] The *Decision support* component collects all possible routes from the *Geo-spatial database infrastructure* as well as the last snapshot of values of relevant functional properties for those routes which can be produced dynamically by the *Data federation* component or retrieved from the *Knowledge base* (rules 1-3).

Afterwards the Decision support component relies on the Clingo4 ASP reasoner to compute the optimal routes that satisfy the user's reasoning request best. In the current implementation of the Decision support, the user will receive at most 5 optimal routes.

Figure 19 a) depicts the user interface where the routes computed by the Decision support are displayed to the end user.

After the user selects the preferred route, a request is generated to the *Contextual filtering* component in order to identify the relevant events for the use while he/she is traveling. The request includes the following properties:

- Route of interest: the current route of the user
- Filtering Factors: used to filter unrelated (unwanted) events out, and include event's source, event's category, and user's activity, as specified in a user-context ontology.[17] For this particular scenario, the activities included in our ontology include CarCommute (user is traveling by a car), or Walk, or BikeCommute (user is traveling by a bike).
- Ranking Factor: identifies which metric is preferred by the user for ranking the criticality of incoming events. We have currently implemented the Ranking Factor based on two metrics: distance, and gravity of the event. In order to combine these two metrics, we use the linear combination approach, where the user can identify weights (or importance) for each metric.

Similar to the decision support constraints and preferences, the filtering and ranking factors are selected by the domain

[16] Note that this can be fully automated due to the declarative nature of our approach to rule-based reasoning based on ASP.

[17] Note that the ontology can be extended by adding new activities.

expert during the mobile application development stage, but they can be made accessible to the end users.

Once the user has selected one of the routes computed by the Decision support component, the Contextual Filtering component sends a request to the Geospatial Database Infrastructure component to obtain the description of the event streams available on the selected route, as registered at design time by the Event detection component. The Contextual Filtering component uses these descriptions to subscribe to detected events via a Data Bus. In addition, the Contextual Filtering also receives the contextual information of the user (currently including location) from the user/application as a stream. Whenever there is a new event detected by the Event detection component, the Contextual Filtering component filters and assigns the most appropriate criticality (0 if not critical, from 1 to 5 if it is critical) to the new event. If the new event is marked as critical,[18] the user receives a notification and he/she has the option to change the current solution and request a new one or ignore the event.

Figure 19 b) depicts the notification received by the end user, while s/he is traveling and a traffic event is detected on his/hers route.

In addition to the contextual filtering request, the mobile application triggers the *Data federation* to continuously compute the average speed of the cars from the selected route. At design time, the application developer has configured the *Data federation* component to store the meta-data for the traffic sensors and to use the ''EL'' load balancing strategy (starts with one engine instance and creates more instances elastically when all existing instances have reached maximum capacity).

The request generated by the mobile application contains the following fields:

- ep: the query pattern, in this application it is a conjunction of primitive traffic report events,
- constraint: the QoS constraint vector, absence of the constraint results in application of a set of defaulted loose constraints,
- weight: the QoS weight vector, absence of the weights results in equal weights configured to all QoS metrics,
- continuous: true have been selected to compute the average continuously;
- engineType: type of RDF processing engine to be used, can be 'CQELS' or 'CSPARQL'
- aggOp: aggregation operator, which for our particular situation is average.

The *ep* in the request contains the functional requirements for the primitive traffic data streams, e.g. what properties should they measure and what are the locations of the sensors (computed from the route selected by the user). Combining the functional requirements with the QoS constraints and preferences, the *Data federation* component creates the optimal composition plan for the request based on the stream meta-data provided in the knowledge based.

```
SELECT ?obId1 ?obId2 ?v1 ?v2
WHERE { ?p1   a ct:AverageSpeed.
         ?p2   a ct:AverageSpeed.
STREAM <Traffic226> [range 3s ]
         {?obId1 a ?ob.
          ?obId1 ssn:observedProperty ?p1.
          ?obId1 sao:value ?v1.}
STREAM <Traffic439> [range 3s ]
         {?obId2 a ?ob.
          ?obId2 ssn:observedProperty ?p2.
          ?obId2 sao:value ?v2.}
}
```

Listing 6. Sample CQELS query generated from composition plan.

According to the *engineType* parameter specified in the request, the composition plan is transformed into a CQELS or CSPARQL query, as shown in Listing 6. A post-processing is applied to the query evaluation results to aggregate the observation values, using the aggregation operator specified in the *aggOp*.If the *aggOp* is set to empty then no post-processing is invoked.

The Data Federation is a generic component that gives continuous query results over federated data streams. Since it follows a service-oriented approach, the discovery and composition algorithms do not require changes based on specific application domains, as long as the service description model is used by the service providers and consumers.

The domain experts can choose between different default target continuous query evaluation systems (currently CQELS and C-SPARQL are integrated), based on the different characteristics of the application domains, e.g., the average query size, the frequency of data streams and the size of the background knowledge. These factors may affect the performance of the target systems (for more information refer to [42]) and a configuration based on specific scenario could be beneficial, but it is not mandatory.

V. CONCLUSIONS AND FUTURE WORK

Providing enhanced services to citizens while cities are growing due to urbanisation, and while resources are limited demands for a more intelligent use of the existing resources. The cities have started to deploy sensor and actor devices in their environment, e.g. intelligent lighting, and observation and monitoring devices to collect traffic, air quality and water/waste data. However, the current focus is mainly on collection, storage and visualisation of the datasets with an emphasis on high performance computing and visual computing solutions. While the recent efforts in this area have enabled emerging technologies and solutions to develop novel techniques for smart city applications and use-cases scenarios, there is however a gap in providing efficient and scalable methods that enable (near)real-time processing and interpretation of streamed sensory and social media data in smart city environments.

[18]Note that we currently provide all events marked with criticality higher than 0, but this can be changed by fixing a different threshold or limiting the notification to the top-k events.

This paper proposes a framework for large-scale data analytics to provide information in (near-)real-time, transform raw data into actionable information, and to enable creating ''up-to-date'' smart city applications. To deal with the heterogeneity of the datasets a virtualisation technique is employed using *Data Wrappers*. However raw data will not be directly machine-readable and it hinder automated interpretation of the collected data. In our work, the datasets are semantically annotated that enable interoperability and provide machine-readable/interpretable representation of the data streams. The varying quality of the data is considered from the beginning by providing quality measures. Data stream aggregation and fault recovery techniques are used to enhance the quality-aware access and processing of the data streams. To extract events from the large data sets in (near-)real-time, complex event processing and contextual filtering methods are used.

The proposed framework has been demonstrated in the paper by a smart Travel Planer application. The main contributions of this work include integrating of heterogeneous data streams, providing interoperability, quality analysis, (near-) real-time data analytics and application development in a scalable framework. The CityPulse components have been developed as reusable entities and are provided as open-source software that are available via the CityPulse github repository (https://github.com/CityPulse).

The CityPulse middleware components are also reusable in different application domains and are provided as open-source.

In order to reduce complexity and time for developing new applications a set of APIs is provided by each of the CityPulse components. This way the developers of services are able to abstract the complexity of the CityPulse middleware and are not bound to use specific technologies for the implementation.

The future work will focus on evaluation of the proposed framework for (near-)real-time city data analytics in different domains. The framework will be also used to provide data access user interfaces and prototype applications for smart city use-cases in the city of Aarhus and the city of Brasov.

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