Multiscale building modelling and energy simulation support tools

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ABSTRACT: Building and district modelling (BIM, CityGML…) are key technologies for the deployment of energy efficiency strategies at building and district level, from the initial stages of planning and design to the operation and maintenance ones. These technologies allow satisfying the interoperability requirements that facilitate the cooperation among the multiple stakeholders and provide the framework to develop more intelligent tools. This paper introduces five complementary European R&D projects in which TECNALIA is collaborating, very good examples of innovative systems based on these concepts. MOEEBIUS enhances passive and active building elements modelling approaches enabling improved building energy performance simulations. HOLISTEEC focuses on building multi-physical simulations considering the neighborhood context. FASUDIR exploits the high potential of GIS tools for urban sustainability analysis and accurate building energy performance evaluation. EFFESUS integrates district and building scales in historic districts. OPTEEMAL develops a platform at district level, based on an IPD approach.

1 INTRODUCTION

Increasingly there is a need for interactive and user-friendly decision support tools that enable analysis of the impact of the building energy oriented projects on the sustainability of the urban district in a holistic way, and facilitate the necessary communication mechanisms between the multiple stakeholders that are involved in the process (Egusquiza et al. 2014).

The five projects presented in this paper aim to develop the knowledge, strategies, decision support models and tools to meet the challenges of linking the strategic urban level to the executive building level from a multiscale perspective considering innovative energy simulation approaches.

At building level the main research focus of the MOEEBIUS (Modelling Optimization of Energy Efficiency in Buildings for Urban Sustainability) project is on developing tools to monitor and assess actual building energy performance, considering relevant factors such as user behaviour, complex energy systems performance and weather forecast, and to be able to predict accurately building energy loads and consumption along the whole lifecycle..

The HOLISTEEC (Holistic and Optimized Life-cycle Integrated SupporT for Energy-Efficient building design and Construction) project aims to provide a collaboration platform for performance-based building design during the entire life-cycle, based on multi-physical simulations (energy, acoustics, lighting and environment) from early design phases and considering interactions with the neighbourhood, built upon IFC (Liebich et al. 2015) and CityGML (Gröger et al. 2012) standards, and using BCF (BIM Collaboration Format) mechanism.

The FASUDIR (Friendly and Affordable Sustainable Urban Districts Retrofitting) and EFFESUS (Energy Efficiency for EU Historic Districts' Sustainability) projects propose a seamless integration of district and building scales through a unique data model based on CityGML standard, combining the high potential of GIS tools for urban sustainability analysis with an accurate energy performance evaluation at building level to allow the selection of the most suitable strategies on energy retrofitting interventions in districts.

The OPTEEMAL (Optimised Energy Efficient Design Platform for Refurbishment at District Level) project aims to develop a design platform, based on an IPD (Integrated Project Delivery) approach and supported by the utilization of BIM models, for an integrated, optimized and systemic energy oriented refurbishment at district level.

2 MOEEBIUS PROJECT

MOEEBIUS project (www.moeebius.eu) aims to reduce the gap between energy prediction and real/measured energy performance of buildings to values below 10%, by addressing occupants' behaviour, real HVAC (Heating, Ventilation and Air Conditioning) performance and real weather conditions both at the building energy performance simulation (commissioning), as well as during the operation phase (real-time optimization on the basis of fine-grained control and automation).

MOEEBIUS solutions will be validated in real-life conditions over an extensive 20-month pilot roll-out period (that includes equipment and systems installations, base-lining activities, models and systems calibration and actual validation of MOEEBIUS in real-life situations) in a variety of buildings (office, retail, educational, sports, residential, hotel) and building blocks (considering their interactions in energy performance optimization) under different environmental, social and cultural contexts in three dispersed geographical areas (London in UK, Mafra in Portugal and Belgrade in Serbia).

2.1 *Modelling approach*

MOEEBIUS introduces a holistic modelling approach that focuses on appropriately addressing and accurately understanding all sources of uncertainty and inaccuracy in building performance assessment.

MOEEBIUS adopts a hybrid approach that combines white-box modelling techniques (at the level of BIM) with black-box modelling approaches (focusing on occupants' behaviour) to deliver an innovative system that captures the real complexities of actual buildings and allows for the correct understanding of user behaviour's impact.

Enhanced, accurate and dynamic behavioural (individual and/or group) profiles complement improved static BIM models (with reduced simplifications and able to accommodate life-cycle assessment and life-cycle cost parameters to enable advanced and optimized predictions through, the appropriately configured, MOEEBIUS building energy performance simulation engine.

2.2 *Simulation approach*

MOEEBIUS uses a two-step calibration process of dynamic simulation tools that considers as-built characteristics, set-points, local real weather data, real occupancy (first step) and sub-metering HVAC/lighting data, real indoor temperature (second step).

The MOEEBIUS performance optimization mechanisms are based on an enhanced version of the already available open-source and widely used EnergyPlus simulation engine. It accommodates enhanced algorithmic concepts for bringing together improved BIM models, semantically improved with DER (Distributed Energy Resources) models and dynamically updated with occupant behaviour profiles, schedules and weather forecasts and utilizing them in building performance simulation iterations towards offering optimized performance predictions of high accuracy.

Even though modelling comprises a focal point of MOEEBIUS, the core outcome and main innovation introduced in the project lies upon the MOEEBIUS dynamic assessment engine. At building level, the dynamic assessment engine serves two distinct, but also interrelated functions: (i) fault detection and diagnosis and (ii) distributed fuzzy model predictive control.

Simulation outputs and real-time measurements from BEMS (Building Energy Management Systems), the MOEEBIUS wireless sensor network and external sources (weather data), are fed to the dynamic assessment engine and comparatively assessed for the identification of performance deviations and their root causes. Through fault detection and diagnosis, the dynamic assessment engine is able to recognize whether the building is beginning to operate sub-optimally; and proactively identify specific performance trends at different spatio-temporal granularity (e.g. abnormal HVAC consumption increase in a specific room) that could progressively lead to significant performance deviations. Subsequently, it is able to drill-in and analyze parameters affecting the deviating metrics (e.g. ambient/behavioural trends) to define the root cause of the evolving deviation.

The definition of the root cause triggers the activation of an innovative distributed fuzzy model predictive control engine. The engine allows for short-term prediction of the building performance outcome (every few minutes) under alternative automated control strategies that aim at mitigating the identified deviation. This is achieved by adapting the operation (self-adaptation) of the building to performance targets, while preserving occupants' comfort and health at acceptable levels. Optimization performed through the dynamic assessment engine is an iterative and continuous process that allows for the prompt identification of deviations (continuous assessment through the fault detection/diagnosis) and execution of short-loop, few-minutes long simulations for the definition of optimal automation strategies.

In case no relevant root cause is identified, the problem is passed to the predictive maintenance and retrofitting advisor modules, for further investigation and definition of alternative maintenance and retrofitting actions, respectively, to effectively mitigate the identified deviation. To enhance user experience in this area, a virtual reality environment using BIM information (3D BIM mapping) and mobile device sensors (for location tracking) effectively complements the operation of the maintenance subsystem with a highly intuitive, friendly and useful user interface.

The multiscale energy simulation focuses on real time optimization of energy demand and supply with the objective of reducing the difference be-tween peak power demand and minimum night time demand. Low-level information and intelligence (building) will be uplifted to the high-level (district) towards assessing (in real-time) the energy performance and demand flexibility at the level of blocks of buildings. This is achieved through an innovative forecasting, aggregation and flexibility module that enables real-time dynamic virtual power plants formulation with enhanced aggregated flexibility capabilities to participate in event-, time-, location- or price-based demand side management strategies.

2.3 *Innovation*

The main innovation introduced in MOEEBIUS is the holistic modelling approach that focuses on appropriately addressing and accurately understanding all sources of uncertainty and inaccuracy in building performance assessment. Dynamic models reflecting user comfort and overall behaviour in the built environment, enhanced DER and district heating models and short-term weather forecasts feed the MOEEBIUS building energy performance simulation system, allowing for predictions of high accuracy.

Novel end-user applications and decision support tools developed in the project are oriented to (i) real-time optimization through automated control, (ii) predictive maintenance diagnostics and decision making, including sanitary maintenance of HVAC systems to preserve high indoor environmental quality and (iii) advanced retrofitting advising through automated criteria-based configuration, evaluation and selection of optimal integrated retrofitting interventions.

2.4 *Acknowledgements*

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3 HOLISTEEC PROJECT

The central aspect of HOLISTEEC (www.holisteecproject.eu) is to enable multi-physical simulations and optimization during all building life-cycle design stages, relying on a collaborative and loop-based design methodology (Delponte et al. 2014, Mazza et al. 2015).

In order to achieve this goal it is essential that (i) simulation tools are adapted to models in different LOD (Level of Development), (ii) there is a proper interoperability between BIM and simulation that can handle model changes and versions, (iii) collaboration mechanisms are implemented to support open workflows and loop-based design between designers and simulation experts in different disciplines (energy, acoustic, lighting and environment) so that conflicts can be evaluated and different decisions can be tracked back and (iv) KPIs (Key Performance Indicators) definitions and requirements which cover all disciplines are accordingly adapted to the design phases and can be continuously monitored.

HOLISTEEC will be validated in four real building projects provided by end-users in the consortium. Targeted projects cover different countries and climates (Turkey, Finland, the Netherlands and Belgium), different stages (conceptual designs, detailed designs, retrofitting projects, etc.) as well as different uses and typologies (residential and holiday complexes, office buildings, student dormitories, etc.).

3.1 *Modelling approach*

In order to achieve an interoperability mechanism between spatial domains and technical disciplines a neutral simulation model based on XML (SIM model) is defined. Algorithms have been developed to extract and adapt the geometry and topology from the BIM model (IFC) and the neighbourhood model (CityGML) and combine into a single source which accommodates different representation details.

In addition, the model adapts to the building LOD in terms of building products and systems. Thus, in early phases the SIM model matches the basic composition information provided in the BIM (perhaps only a name or tag representing the typology) with performance information provided by generic e-catalogue products. In detailed phases (higher LOD), the details of product physical properties can be directly taken from IFC material layers. An e-catalogue system adapted to various LOD and supporting both generic and vendor-specific products is developed as part of the HOLISTEEC platform.

The generation of simulation models is a three-step process: (i) an automatic generation of the aforementioned neutral or "raw" SIM model with geometry/topology suitable for various disciples, (ii) A loop process, where the SIM model is linked to e-catalogue products creating a set of SIM model variants or configurations. It is a user-driven process but supported by HOLISTEEC services and user interfaces and (iii) transformation of those simulation variants into different input files for each of the provided simulation engines. In some cases tools provided by project partners and tailored to HOLISTEEC are used, in other cases existing third-party engines.

3.2 *Simulation approach*

In relation to energy simulation, the multiscale issue is targeted by providing two approaches, each one focused in different users, different project phases and different decisions. For early stages a neighbourhood level simulation is offered, intended for early decisions by the architect (e.g. building shape type, orientation, glazing ratios). Influences of the surrounding environment are considered in terms of shadowing, reflections, etc. but also impacts of the target building into the rest in a bidirectional way.

The main innovation for this approach is to extend the capabilities of an existing building scope simulation engine like EnergyPlus for urban scale simulation. Thus, the CityGML model is transformed into the aforementioned SIM model. For the target building envelope is created (external wall, windows, roof…) and when there is not yet information about windows rules for glazing ratios creation are defined. Storey-level thermal zones are then automatically generated. Other buildings are considered as shadowing surfaces. To reduce the computational resources of a complex urban model filtering mechanisms are implemented to consider only relevant shadowing surfaces depending on distance and height. The process is iteratively repeated, considering a different target building in each iteration, yielding from one city model a set of EnergyPlus simulations (one per target building), whose results are then combined and visualized in 3D. Different design variants can be tried and compared.

The second approach for energy simulation focuses on a single building (the target one) and relies on a detailed representation of the building geometry, internal zone partitioning and details about HVAC systems, as well as more detailed occupancy and behavior models. In this approach, the core of the information to the SIM model comes from IFC and is suited for more advanced LOD, oriented to consultants or simulation experts with a deeper insight, since further manual interaction and enhancing of the SIM model could be required. Existing software implementations are adapted to the platform and data models.

3.3 *Innovation*

Energy simulations are considered for a variable range of levels of detail through an intermediate neutral SIM model which can combine several building and several representation modes for the same building, merging information coming from either IFC or CityGML, which then is converted to various simulation engines targeted to various end users and project stages.

Neutral SIM models are transformed to different existing building simulation engines through custom adaptations. In the case of the neighbourhood, the main innovation consists of the extension of building scope engines (EnergyPlus) for urban extent.

3.4 *Acknowledgements*

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4 FASUDIR PROJECT

FASUDIR (www.fasudir.eu) main result is the Integrated Decision Support Tool (IDST), developed to help decision makers to select the best energy retrofitting strategy to increase the sustainability of the whole district (Mittermeier et al. 2014). The IDST features a 3D graphical user interface in order to facilitate the interaction between the multiple stakeholders involved in the decision making process (Romero et al. 2014).

FASUDIR IDST is being validated in three different European urban developments that are representative of different district typologies that are common in Europe, and especially in need of energy retrofitting initiatives (Santiago de Compostela in Spain, Frankfurt in Germany and Budapest in Hungary).

4.1 *Modelling approach*

In FASUDIR a unique building/district energy model, which enables the documentation of all the information required for the development of the FASUDIR IDST, is designed and developed.

The data model structure is based on the CityGML standard extended with domain specific information. Data model compiles the required information for KPI calculation at both levels (building and district). Data model is divided into CM (City Model) and SM (Simulation model). The CM, which is based on CityGML, contains all the data representing the current state of the district. All the parameters required for triggering the required simulations are stored into the SM.

CM is completed with the indicators information (KPIs) after their calculation to determine the current state of the district. The information collected into the FASUDIR CM is grouped into the different city elements represented into the CityGML standard (building, transportation, vegetation, city furniture, etc.). CM extends CityGML with required ADE (Application Domain Extensions) in order to represent all the required information. The way to access the FASUDIR CM is through the use of standard web services defined by OGC (Prieto et al. 2013).

4.2 *Simulation approach*

Once the building/district energy model is created, the simulation process can start through the simulation server. Instructions and data are sent to the simulation server through the user interface and record data from the CM database are received. SM gets the information from the CM and adapts it to the needs of the simulation tool to be used (IES <VE>). The results of the simulation of different variants are represented by the results of the KPIs and are stored in the CM. The SM is generated on the fly for the simulation.

The simulation server creates/maintains the simulation job queue through the simulation scheduler for the calculation of KPIs, creates batch instructions for each job (e.g. solar simulations + thermal simulations + value) and returns data to the CM database once simulations are completed to be stored in the database.

4.3 *Innovation*

The software enables modelling the district and building with an adequate level of definition, in such a way that evaluation results are precise enough, but the input data to define the retrofitting project is easily supplied. FASUDIR model is based on CityGML and is supported by GIS capabilities and accurate energy performance evaluation at building level.

4.4 *Acknowledgements*

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5 EFFESUS PROJECT

The main output of the EFFESUS project (www.effesus.eu) is a DSS (Decision Support System), a software tool, which includes all the parameters needed to select suitable energy efficiency interventions for historic districts (Eriksson et al. 2014). The main software modules developed in EFFESUS are: a multiscale data model, a categorization tool, a repository on technologies and the DSS

EFFESUS DSS is being validated in two different European urban developments that are representative of different district typologies that are common in Europe, which are Santiago de Compostela (Spain) and Visby (Sweden).

5.1 *Modelling approach*

The multiscale data model defined in EFFESUS is a virtual 3D city model based on the CityGML standard. The multiscale data model provides a representation of the urban information at different levels (from the city level to the building component level). It represents graphical appearance of the city as well as semantic or thematic properties.

A four step methodology has been defined for the 3D geometry generation and storage. Generation methodology is based on available data sources (footprints, cadaster, LiDAR, images, etc.). As a result of the generation process terrain, roads, green areas and buildings at different LoD (Level of Detail) are obtained.

The categorization tool provides the user an easy and intuitive way for the identification of building typologies in an urban district. The categorization tool is based on data included in the EFFESUS data model. Algorithms for building categorization have been implemented based on the building stock categorization methodology defined within the project. Geometry of the multiscale data model has been used for the visualization of the building typologies as well as the most representative building of each typology. The user interacts with the tool editing properties of representative buildings as well as editing parameters and thresholds for categorization. EFFESUS DSS is based on the identification of different typologies of building stock.

5.2 *Simulation approach*

The DSS software tool is based on a holistic methodological framework for the assessment of energy-related interventions in built cultural heritage. This methodological framework for decision-making aims to identify and classify actions according to: compatibility with the cultural significance, energy saving, habitability and economical, technical and legislative feasibility. The methodology has been developed at two scales: the urban scale and the building level. The methodology defines the specifications for its implementation in the expert system of the DSS.

The required information for the decision making process is based on the “simple hourly calculation procedure” included in the EN ISO 13790:2008 (ISO 2008). This procedure has been selected because it has been proved to generate satisfactory results with a limited input data requirement, which is crucial for EFFESUS taking into account the scale in the decisions.

An EPDE (Energy Performance Domain Extension) has been designed. It has been implemented as an ADE for the CityGML standard. This ADE has the purpose to storage the information regarding the energy related parameters that will allow proper decision making. The calculation procedure and the required input data has to provide enough accuracy and flexibility to model the building stock of any district, aiming to accomplish this calculation without relying heavily on a large amount of input data.

The EPDE includes in-formation at different scales: district, building, building envelope (wall, roof, ground, etc.) and building installation (demand and generation installations). Information related with climate is referenced at district level, information related with geometry, occupancy and use is set at building level, while material properties, type and size of the windows and relation between opaque and opening areas must be identified at the level of the envelope elements of the building. Other element relevant for the identification of the energy efficiency of the building is related with the energy installations: type, efficiency, etc.

5.3 *Innovation*

The EFFESUS data model has been generated from different available data sources (geometric and semantic). The categorization tool provides the user an easy and intuitive way for the identification of building typologies in an urban district.

A CityGML ADE has been designed and implemented in order to structure and storage all the required information that is not included in the CityGML core. Information is structure according to the representative-ness of the elements of the historic district for the energy assessment and management.

5.4 *Acknowledgements*

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6 OPTEEMAL PROJECT

The objective of OPTEEMAL project (www.opteemal-project.eu) is to develop an optimized energy efficient design platform for refurbishment at district level. The platform delivers an optmised, integrated and systematic design based on an IPD approach for building and district retrofitting projects. This is achieved through development of holistic and effective services platform that involves stakeholders at various stages of the design while assuring interoperability through an integrated ontology-based DDM (District Data Model).

OPTEEMAL will be validated in three different urban districts in three European cities, which are San Sebastian (Spain), Lund (Sweden) and Trento (Italy).

6.1 *Modelling approach*

The DDM plays a key role to ensure the interoperability between different standard data models. The proposed DDM is a comprehensive semantic framework which facilitates the intertwining of standard data models with domain specific ontologies.

The DDM will be implemented as a set of interoperable data repositories. A data repository is a DDM component whose goal is to manage the information required to carry out the platform's processes. Furthermore, the outputs of these processes as well as the users' inputs are stored in the data repository.

At this stage of the project five repositories have been envisaged: BIM repository, city repository, contextual repository, ECM (Energy Conservation Measures) catalogue and platform database.

BIM repository stores the models of the buildings of the case studies. The final enhanced BIM models generated by the platform will also be stored in this repository. The number of BIM models to be included in the repository will depend much on the availability of those models. An optimum scenario will include one BIM model for each building, however currently it is not very common to have such models, even less probable for existing buildings. In such case the minimum number of BIM models will be one and will be desirable to have at least a BIM model for each building typology.

City repository stores a district model. The buildings represented in this model are linked to the BIM models stored in BIM repository.

Contextual repository stores the contextual data of the case studies such as weather data, economic indicators, social data, and environmental data, among others. These data are linked to the data stored in BIM and city repositories.

ECM catalogue stores the energy conservation measures used to generate the refurbishment scenarios to be optimized by the OPTEEMAL platform.

Platform database stores the data generated within the platform such as DPIs (District Performance Indicators), platform users, scenarios, user's inputs (e.g. barriers, targets, boundaries, priorities) and simulation models (energy, economic, environmental…) automatically generated.

Assuring the interoperability between heterogeneous information is a major requirement of the OPTEEMAL platform. In addition to the use of standards like IFC and CityGML, it is necessary to create links between different data models to perform the functionalities foreseen in the platform. Three different types of link can be identified at this stage: (i) links between different data models in different repositories describing the same district, (ii) links between objects into different data models (e.g. a building into the IFC and CityGML) and (iii) links between alternative retrofitting scenarios describing the same building or district.

6.2 *Simulation approach*

In the OPTEEMAL platform, the current scenario is represented by the district data (CityGML model), the building data (BIM model) and the contextual data (urban data, climatic data, energy and environment data, social data, etc.). To complete the description of the current situation, according to the targets, boundaries, barriers and the prioritization criteria, for the refurbishment of the case study provided by the user, the platform calculates the set of DPIs applicable to the current situation of the district.

IFC data model is defined for being used in a broad range of applications and domains. Due to the vast extent of IFC specialized domain application, models shall be defined as an intermediate step between the BIM and the simulation engine. This intermediate step is represented in OPTEEMAL by the simulation models. It will be necessary to generate different simulation models for each simulation tool (EnergyPlus, CitySim, NEST and OPTEEMAL tools).

The approach in OPTEEMAL is to use IFC and CityGML as common data models for input and output of the district and building information, which will be further transformed into simulation models tailored for each domain and simulation engine, keeping the traceability and mapping between elements and concepts with the original models. According to the list of DPIs and the way they are grouped into categories, 6 domain models are identified: energy model, environmental model, comfort model, economic model, social model and urban model.

6.3 *Innovation*

In OPTEEMAL, the DDM will be modeled using IFC and CityGML standards linked with domain specific ontologies. Based on the DDM, different simulation models for the simulation tools identified in the project will be generated in the process to DPI calculation. As a result of the optimization process an enhanced BIM model including most suitable ECM will be obtained.

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7 CONCLUSIONS

The five projects described in this paper provide complementary approaches to building modelling and energy simulation with multiscale perspective.

MOEEBIUS addresses the challenges and factors that hinder the capabilities of current simulation and control frameworks to provide highly accurate predictions and fine-grained optimization considering the complexities induced during buildings’ and districts’ real time operation.

HOLISTEEC addresses the issue of enabling multi-physical simulations in all design stages, flexibly adapting to the available information in each stage and covering different spatial extents. This is achieved through a neutral SIM model, which integrates information from IFC and CityGML by providing automatic geometry and topology transformation routines common to all disciplines. Additionally, an intelligent e-Catalogue system is provided for providing different performance simulation scenarios in each phase. Finally exporters to specific simulation engine input files are developed. All the actors involved collaborate using BCF standard.

Integrated approaches presented in FASUDIR and EFFESUS with intuitive user-friendly software represent an innovative alternative for decision-making to prioritize the action to be taken and to improve the sustainability of urban districts and their subsequent management. The strategic management of the information generated by a city should be a key part of this process. The development of data models based on the international CityGML standard allows GIS and BIM concepts to be integrated within the same model. The information contained in the model is unique and can be used to develop various applications that the different agents (city managers, technicians and members of the public) employ.

OPTEEMAL provides a holistic platform to design efficient refurbishment projects at building at district level supported by a comprehensive ontologies-based framework for district information representation based on the relation of existing semantically enriched data models (CityGML, IFC) with existing ontologies/data models in the main fields for urban sustainable regeneration. The interoperability among inputs and outputs of the platform with external tools is assured by the definition of simulation models.

Consequently, this collection of projects visualizes the revolution in building and cities design and management procedures that is already starting. The growing complexity of buildings and cities and the urgency to make them more sustainable requires the development of knowledge based design and management tools supported by powerful data models. The combination of the IFC/BIM (building dimension) and CityGML (district and city dimension) has demonstrated that is the most promising approach, providing the modeling detail that is requested by each stakeholder and seamless integration between building and city.

Finally, one of the main challenges encountered that needs further research and improvements is to reach a successful integration and interoperability between different approaches: (i) physical models (BIM/IFC and CityGML) vs simulation models (which rely on a conceptual zone-based geometry definition) and (ii) adaptation of simulation engines usually focused on design aspects to accommodate real-time data.

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