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ARCHITECTURE MODEL OF THE GAS METERING VIRTUAL POINTS AUTOMATION SYSTEM

The article presents the results of the research into the architectural model for an automated gas metering system based on the concept of virtual points of gas metering, which is an abstraction layer above physical gas metering devices providing possibilities for great automation and optimization as well as flexibility and precision in the domain of centralized gas metering. The primary objective of the research is to design an optimal architectural model that satisfies the requirements and constraints of the system's conceptual model. This study delves into the process and describes the result of architectural model creation by covering the following aspects: defining system components and their responsibilities, assigning behaviors to the components, defining cross-component and external interactions, designing data models as well as providing API and communication solutions. Additionally, the research also focuses on the basic external interactions and infrastructure considerations necessary for the operation of the automated system. A significant portion of the research is dedicated to addressing specific challenges inherent in gas metering automation. These challenges include the prediction of gas calorific values, determining the temperature at the points of gas consumption, and the calculation of monthly gas usage in kilowatt-hours. By addressing these issues, the research ensures that the architectural model is completed and includes solutions for the domain problems at the scale of the architecture. The solutions proposed for these challenges are integrated into the overall architectural model, providing a robust framework for future research into the topic as well as a basement for the implementation of an accurate and efficient centralized gas metering automation system. Some of the solutions developed during the research lay on the line between software architecture and user experience design. Also, the research scope includes the infrastructural model required for the automated system to function optimally. This includes encompasses both infrastructure-centric and application-centric models, presenting different viewpoints on the reference infrastructure for the optimal system operation.

Keywords: natural gas, virtual points of gas metering, architectural model, conceptual model, virtual temperature points, gas metering.

ПОЛАТАЙКО ІГОР
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АРХІТЕКТУРНА МОДЕЛЬ СИСТЕМИ АВТОМАТИЗАЦІЇ ВІРТУАЛЬНИХ ТОЧОК ЕНЕРГООБЛІКУ ГАЗУ

Стаття представляє результати дослідження архітектурної моделі для автоматизованої системи обліку газу на основі концепції віртуальних точок обліку газу, яка є рівнем абстракції над фізичними приладами обліку газу, забезпечуючи можливості для значної автоматизації та оптимізації, а також гнучкість і точність у сфері централізованого обліку газу. Основна мета дослідження полягає в розробці оптимальної архітектурної моделі, яка відповідає вимогам і обмеженням концептуальної моделі системи. Це дослідження вникає в процес і описує результат створення архітектурної моделі, охоплюючи наступні аспекти: визначення компонентів системи та їхніх обов'язків, закріплення поведінок за компонентами, визначення взаємодій між компонентами та зовнішніми елементами, проектування доменних моделей даних, а також рішення щодо API та комунікацій. Крім того, дослідження також зосереджується на основних зовнішніх взаємодіях та інфраструктурних аспектах, необхідних для функціонування автоматизованої системи. Значна частина дослідження присвячена вирішенню конретних викликів, властивих автоматизації обліку газу. Ці виклики включають прогнозування калорійності газу, визначення температури в точках споживання газу та розрахунок місячного споживання газу в кіловат-годинах. Знаходячи рішення для даних проблем, дослідження забезпечує завершення архітектурної моделі та включає рішення для проблем домену на рівні архітектури. Запропоновані рішення для цих викликів інтегровані в загальну архітектурну модель, забезпечуючи міцну основу для майбутніх досліджень з цієї теми, а також базу для впровадження точної та ефективної автоматизованої системи централізованого обліку газу. Деякі з рішень, розроблених під час дослідження, знаходяться на межі між архітектурою програмного забезпечення та дизайном користувацького досвіду. Крім того, рамки дослідження включають в себе інфраструктурну модель, необхідну для оптимального функціонування автоматизованої системи. Вона охоплює як інфраструктурно-орієнтовану, так і програмно-орієнтовану моделі, представляючи різні точки зору на еталонну інфраструктуру для оптимальної роботи системи.

Ключові слова: природний газ, віртуальні точки обліку газу, архітектурна модель, концептуальна модель, віртуальні температурні точки, облік газу.

General problem statement

Currently, in Ukraine, 10 million household gas meters with mechanical metering devices are installed. A significant portion of these meters are not equipped with systems for compensating for natural gas temperature variations. This absence of compensation mechanisms results in an inability to ensure precise and financially efficient measurements of the volume of gas consumed, particularly when expressed in energy units, as required by existing regulatory documents [1].

Given the limitations of the current metering infrastructure, it is evident that the system is not fully capable of achieving the level of accuracy that modern regulations demand. Accurate gas measurement is crucial for both consumer protection and economic efficiency, especially in the context of energy consumption management.

To address these critical shortcomings, a new approach has been proposed that centers around the use of virtual gas metering points [2]. This innovative concept presents a promising solution to the challenges of gas accounting, not only in Ukraine but potentially on a global scale. By leveraging virtual metering points, this approach could significantly improve the accuracy and efficiency of gas consumption measurement, aligning with both regulatory requirements and broader goals of energy management.

Related research

The conference paper [3] presents the conceptual model of the automation system of gas metering based on the idea of virtual points of gas metering, which is described as a concept in the article [2]. The techniques outlined in references [4] and [5] are applicable for precise and efficient gas volume measurement. Reference [6] discusses the evaluation process for automated systems used in the management and accounting of natural gas energy, which is pertinent for this type of system. References [7] and [8] explore the hybrid method of gas metering and the system for metering natural gas in energy units. Study [9] addresses the online calibration of gas meters within gas control and metering systems. Lastly, references [10], [11], and [12] concentrate on the development of smart gas infrastructures, particularly the metering aspects within such systems.

Research purpose

The purpose or the research is to describe the research results on the optimal architecture model that satisfies the requirements and constraints of the system's conceptual model. The main approach to describing the architecture of the system will follow the steps of analyzing the general system behaviours, that are expected from the system. Then defining the optimal way to split the system into individual components with the behaviors assigned to them, including inter-component communication expressed through behaviors, which arises from the need of one component to invoke the logic on another component in order to fully execute its own behavior or to ensure the consistency of the state of the system as a whole, even if this consistency is eventual. The next steps are transforming components' behaviors into APIs of the components and designing the domain data models for the components, in the scope of which the component logic will operate in order to implement the behaviors. External interactions, required for some of the behaviors will also be described as a separate section. Finally, based on the application level, described with the behaviors, components, APIs, domain data models, and external interaction, the optimal infrastructure for the automated system to operate in will also be presented as part of the architectural model.

Results of the research

Conceptual model review

On the conceptual level [1], the gas metering automation system is based upon the idea of virtual points of gas metering, which is an abstraction that operates above physical gas meters. These virtual accounting points act as meta-meters, reflecting the data of physical meters without being fixed to them [fig 1]. This setup enables the easy replacement of physical meters without affecting the historical data of the virtual ones.

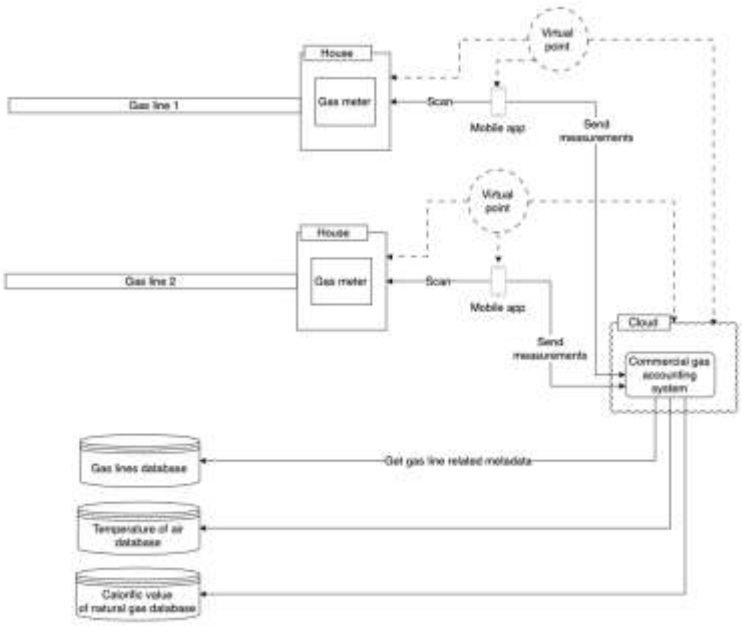

Fig.1. Conceptual model of the system

The virtual points offer real-time measurement values and allow users to view consumption history over time, expressed in cubic meters (m³) and kilowatt-hours (kWh)

Two main categories of users interact with the automated system: House owners (customers) and Controllers [fig 2]. The work of the controller is greatly reduced (up to 90%) compared to the current way the measurements are done due to the automation, which provides a secure way for customers to report gas usage values as well as to share access to the virtual point.

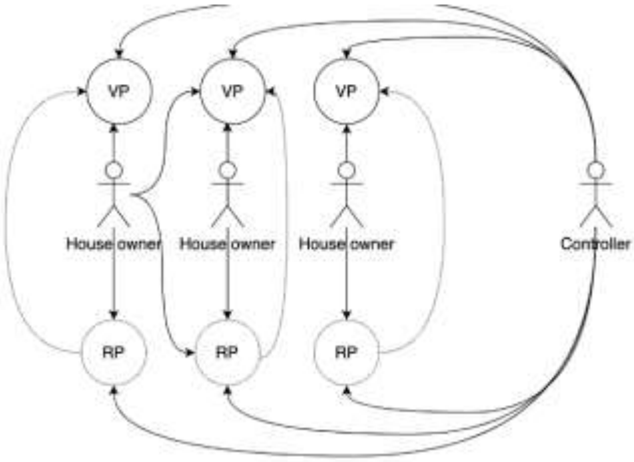

Fig.2. Concept of interactions

From the functional perspective, the system is composed of the following interactions [fig 3] available to the clients via the client mobile application.

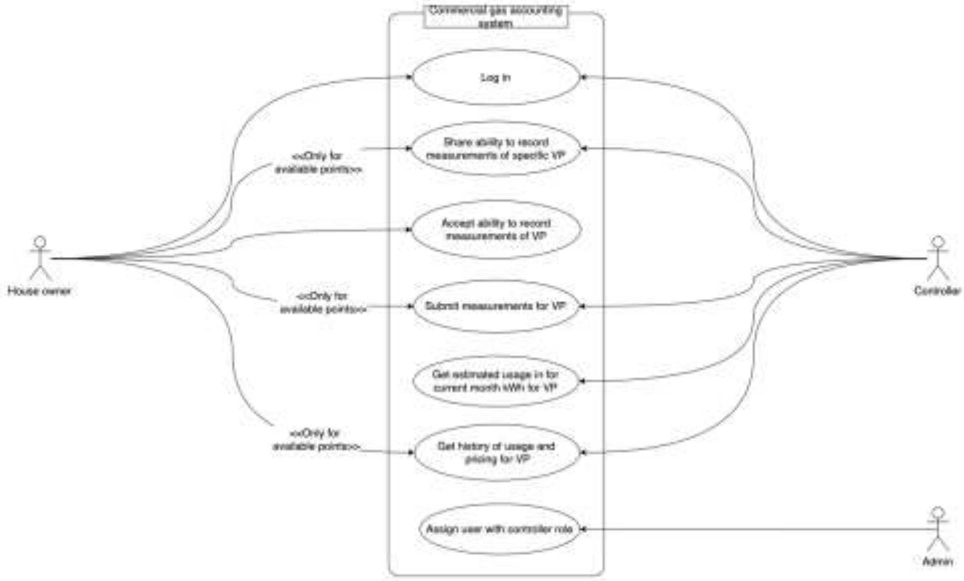

Fig.3. High-level use-case diagram of the system

The conceptual model not only provides the frame for the architectural model but also facilitates the discovery of the problems, that need to be addressed in the solution. Among them are finding the correct temperature at the point of measurement without measuring it with the thermometer, predicting gas calorific values for the days of the month to allow performing usage measurements calculations in kWh before monthly values are officially published, distributing the usage values uniformly across all the days between measurements recordings for the virtual point. All of these problems have to be solved during the research on the optimal architectural model of the automation system.

Virtual temperature points

The calculation of monthly usage in kWh requires both gas calorific values and temperature values for the time period for which the value of monthly usage should be calculated. We are interested in the daily granularity of those values. While gas calorific values are attached to gas lines, so we know the concrete lines have the concrete values, the problem of temperatures is a bit more complicated, because we cannot get a precise temperature in the location of each physical gas meter without placing a physical thermometer near it, which we would like to avoid, because it would open a whole new set of problems like timely reporting of the values, overhead management, etc. The solution to the problem was an idea of virtual temperature points calculated as an approximate temperature value at the point between the points for which we know the temperature: usually, the centers of the cities or districts, that have publicly available official values of the temperature.

First, the relevant points of known temperature have to be selected, based on the rule, that we select the two closest known temperature points and then, also select all the points, that have a distance between them and a virtual temperature point not bigger than the sum of distances between closest known temperature points and virtual temperature point.

$$t_v = \frac{\sum_{i=1}^{n} \quad (z\,t_i)}{\sum_{i=1}^{n} \quad (\frac{dist_{max}}{dist_i})^2}, \tag{1}$$

where tv is the value of temperature at the virtual temperature point, n - number of selected known temperature points, distmax - maximum distance from known temperature point to virtual temperature point from among the selected known temperature points, disti - distance from i-th known temperature point to virtual temperature point from among the selected known temperature points, ti - temperature at i-th known temperature point to virtual temperature point from among the selected known temperature points.

The figure represents the calculation of the temperature in the virtual point based on its distance from the selected known temperature points [fig 4].

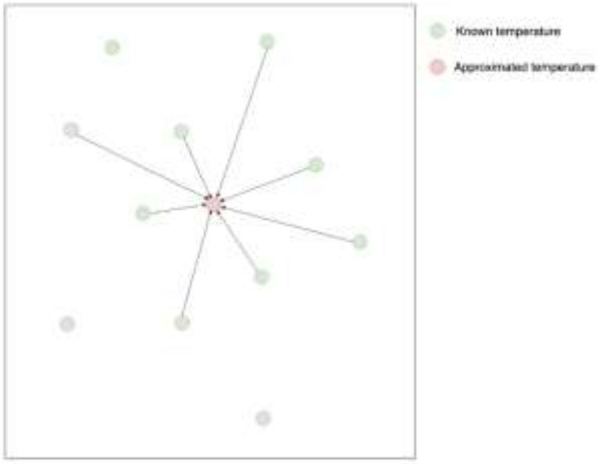

Fig.4. Virtual temperature points

Gas calorific value predictions

Due to the reason, that gas calorific values are published monthly for the whole period of time, but based on the use cases of the mobile client application, consumers and controllers should be able to observe the "current moment" measurements of the virtual metering point, even though such values might be slightly different from the actual usage, calculated based on the official gas calorific values for the different gas lines, published at the end of the month and used by the automated system to compute and record monthly usage for consumers.

In order to incorporate the solution of this problem in the architectural model, an approach with a prediction of gas calorific values, based on historical data is chosen. A dedicated component of the architectural model is responsible for such forecasting based on the machine learning algorithm predicting time-series data with seasonality factors. There are two possible modes of operation for the component:

- Prophet algorithm based predictions. This mode will utilize Prophet which is great for data predictions with seasonality factors, but cannot accept metadata, which means that gas calorific values for each gas line have to be handled by a separate model.
- CNN-QR algorithm based predictions. This mode will utilize the CNN-QR algorithm, which would require more data for training but allows the training of a single model having the whole dataset across different gas lines by converting the gas line marker into a data feature. CNN-QR is a good fit for seasonal data due to the automatic derivation of feature time series.

Monthly usage calculation

Based on the measurements of the physical gas meters, submitted by the consumers or controllers at the points in time, the measurements of the virtual gasmeter are updated: officially at the end of the month and right after the measurements submission with approximate values, based on the predicted gas calorific values.

There are multiple possible strategies for distributing the measured delta (value of gas usage) across the month period:

Uniform distribution of usage throughout the days between the measurement submissions

Using historical data to predict what the usage was on daily granularity. For example to find the correlation between air temperature and usage for the specific month, etc. Further research into this topic can be a research point of upcoming studies.

Independently of the method selected, as a result, the values of the usage for the different days throughout the period of time are obtained. Those values can be used to calculate the monthly usage by summing up the values calculated for the individual days using the formula, also including gas calorific values for the gas line and temperature values for the location of the virtual point on the specific day.

$$E \;=\; \sum_{i=1}^{n} \quad (\frac{T_b}{T_e} \cdot (1{,}0321 - 1{,}13812 \cdot 10^{-4} h) \cdot H_s \cdot V_i), \tag{2}$$

where E - gas usage in kWh, n - number of days in the month, Tb - the base value of gas temperature, Te - temperature of the environment, h - altitude of gas metering location, Hs - gas calorific value for the gas line, Vi - volume of gas consumption on i-th day.

Application level models

Based on the conceptual model of the virtual points of commercial gas accounting automated system and, developed in the scope of this research, solutions for the practical problems of virtual temperature points, gas calorific values predictions, and monthly usage calculation, the research focus can be placed into the architecture model of the system itself.

The model describes the components of the system, their behaviors and interactions, domain data models of the components, API design decisions, interactions with external systems, and infrastructure solutions for the automated system. Overall, this description allows for the full-picture model of the system and can serve as a basis for further research into properties of the architectural model as well as form the basement for the implementation.

First, let's start with the application-level models developed in the scope of the research:

- Components model
- Behaviors model
- Domain data models

Components model

The most essential model to start with the process of research into finding the optimal architectural model for the gas metering automation system is the components model. This model consists of 3 main components each responsible for some part of the system behaviors and related data management:

- Measurements management component. The responsibility of the component is the logic of the measurements submission process and all the related functionalities, e.g. creation and sharing access to virtual points, etc.
- User account management. Responsible for the management of the user accounts.
- Accounting component. Responsible for calculation and keeping a record of gas usage values in kWh and possible integrations with external systems to forward the usage data to them (e.g. centralized energy management systems, consumer billing, etc).

Apart from three main components, there is also a component responsible for predictions of calorific gas values.

Figure 5 presents the component model diagram of the system.

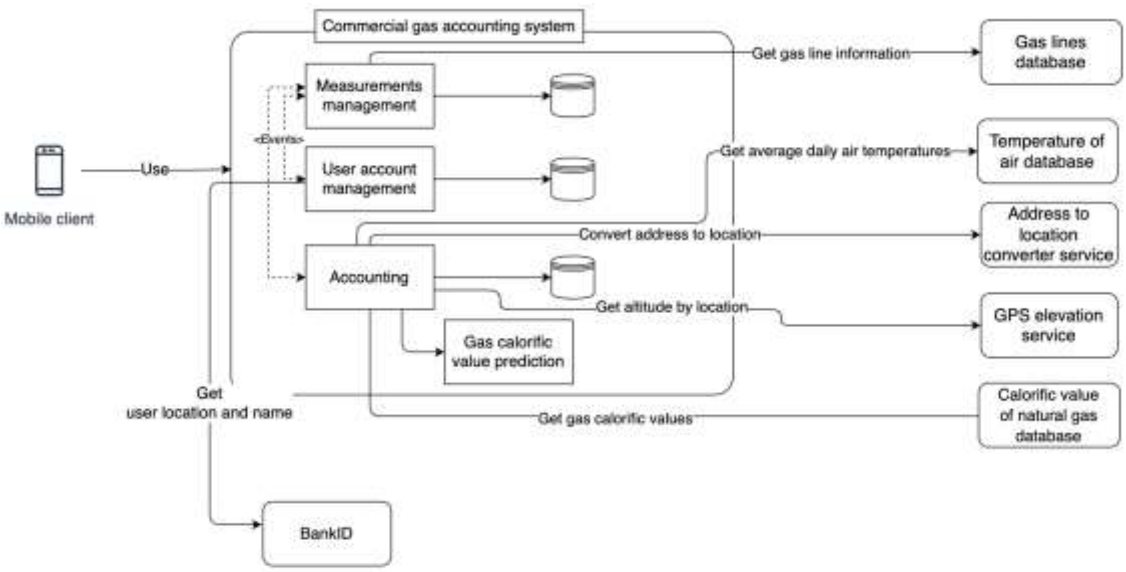

Fig.5. Component model of the system

To keep the consistency of the system as a whole, components use the orchestration variation of the SAGA pattern for asynchronous communication, which is based on the idea, that the component, which is the owner of the top-level behavior, stores the states of the completion of the behaviors it invoked on other components, communicated via events; the whole operation is marked as completed only after all the components responded with the event, that they completed invoked behaviors on their end.

Behaviors and APIs

The model, designed in the scope of this research, consists of four components. To represent the dynamic aspects of the architectural model the behaviors model is constructed for each of the components.

The behaviors of the system are composed of the behaviors of the individual components, that are exposed outside the backend part of the system and available to the mobile application. This type of system behavior is exposed through REST APIs.

The remaining components' behaviors are internal behaviors, which are invoked on component A by component B as the result of executing some behavior by component B. The reason for such interaction might be delegation of work or notification of the changes in the component to keep the rest of the system consistent. In the architectural model of the automation system, these interactions are supposed to be asynchronous to lower the coupling between the components implemented via the message broker.

In order to allow easier onboarding of controller and admin accounts, it was decided to use the same initial login flow as for the consumers: the mobile application will redirect to BankID where the user can grant required permissions and will be redirected back to the mobile application. However, it requires some intermediate steps to the flow (in order to avoid login resulting in a consumer account by default), which split the flow into two steps:

Initial blank account creation as the result of successful first authentication with BankID.

Account creation completion with account type decision.

When the user logs in for the first time, the blank account is created and then, the user can choose the option to proceed to consumer account creation, in the case with all consumers' accounts, or the administrator of the system can convert such blank account into controller or administrator account.

After the successful login, the component will create an asymmetrically signed JSON Web Token (JWT) containing basic information about the user (id, name, surname, role) as well as a list of virtual points to which the consumer is granted access (in case of consumer token) or list of gas lines to which the controller is granted access (in case of consumer token). Due to the asymmetric signature of the JWT, all the components are able to verify the authenticity of the token without any interactions with the "User account management" component, by means of the public key.

External interactions

Some of the behaviors of the system components require interaction with external components. In the scope of this architectural model, external interactions are the following.

The measurements management component interacts with the gas lines database in order to get gas line information from the gas lines database when the "creation of gas line" behavior is invoked on the component, in order to validate/enrich the information provided by the administrator.

The user account management component interacts with the BankID in the scope of the following interactions:

- Get a user token from BankID. Executed as part of single sign-on flow during the "login" behavior.
- Get user-related information from BankID. Executed after "login" behavior to load additional data about the user.
- The accounting component interacts with the following systems:
- Temperature of air database to get average daily air temperatures. Executed by the behavior "Fetch daily temperature values".
- Address to location converter service to convert the address line into the location (longitude and latitude). Executed during the creation of a virtual point in order to fetch data about the location of the point.
- The caloric value of the natural gas database to get gas calorific values for the monthly period. Executed by the behavior "Fetch and store monthly calorific values".
- GPS elevation service to get altitude by the location. Executed during the creation of a virtual point in order to fetch data about the altitude of the point.

Domain data models

The final part of the application-level architectural model of a gas metering automation system based on the concept of virtual points is domain data models. Each component has its own data model to operate with while executing the behaviors assigned. Domain data models on the application level, in the scope of the presented architectural model, match the data models of the database structure design.

The domain data model of the "User account" component [6] is designed to be non-relational, based on a single table or collection, which would contain the data records with account information of four types:

- Blank: the user made an initial login, but the account is not assigned to any type
- Consumer
- Controller
- Admin

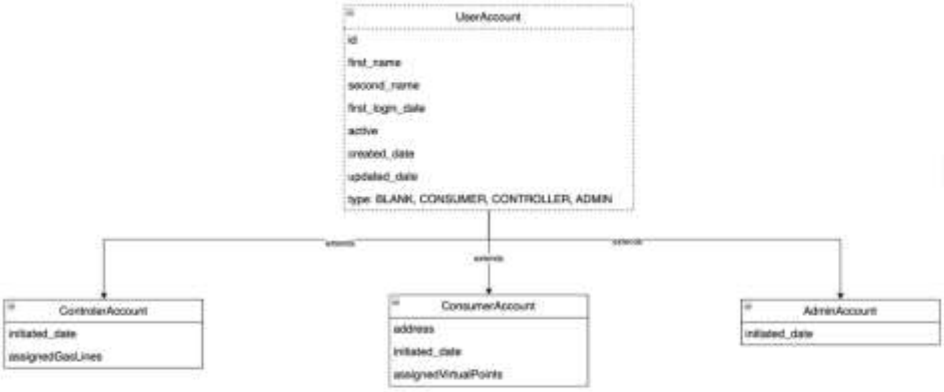

Fig.6. User account component domain data model

In the scope of this research, it was decided that the best way of representing the "Measurements management" domain model component is a relational data model, consisting of the tables containing data relevant to the measurements context [7], as well as other functionality assigned to this component such as sharing access to the virtual point, etc.

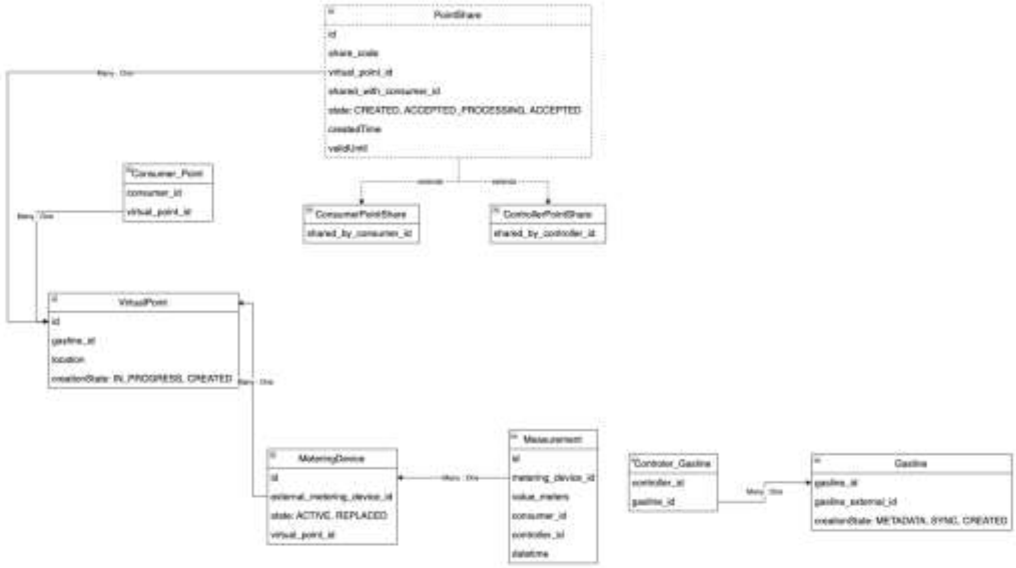

Fig.7. Measurements management component domain data model

The "Accounting" component data model [8] is also based on the relational model and contains data regarding context-specific attributes of virtual points, monthly usages, gas calorific values, temperatures, etc.

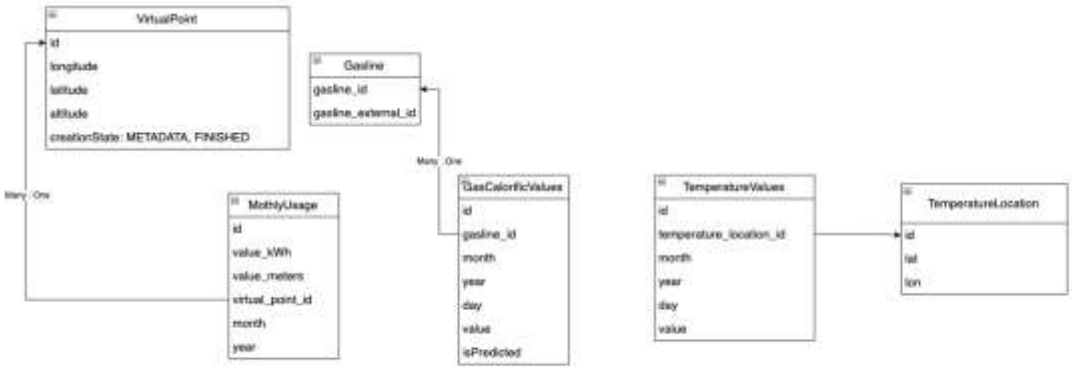

Fig. 8. Accounting component domain data model

Infrastructure level models

The automated system architectural model might be independent of the infrastructure where the system is operating, however, the model would be incomplete if, in the scope of this research, the reference infrastructure level model isn't presented.

The reference infrastructure-level model is based on the cloud infrastructure, which is the most preferred option for high-reliability systems considering the realities of the environment. Amazon Web Services was chosen as a cloud provider for the infrastructure-level reference model. The model [9] presents the networking setup, compute level as well as data level, and other services used by the system to operate. The gas calorific values predictions component is fully based on the software-as-a-service offering from AWS: AWS Forecast, which provides the ability to train and use models based on Prophet and CNN-QR algorithms with minimal effort.

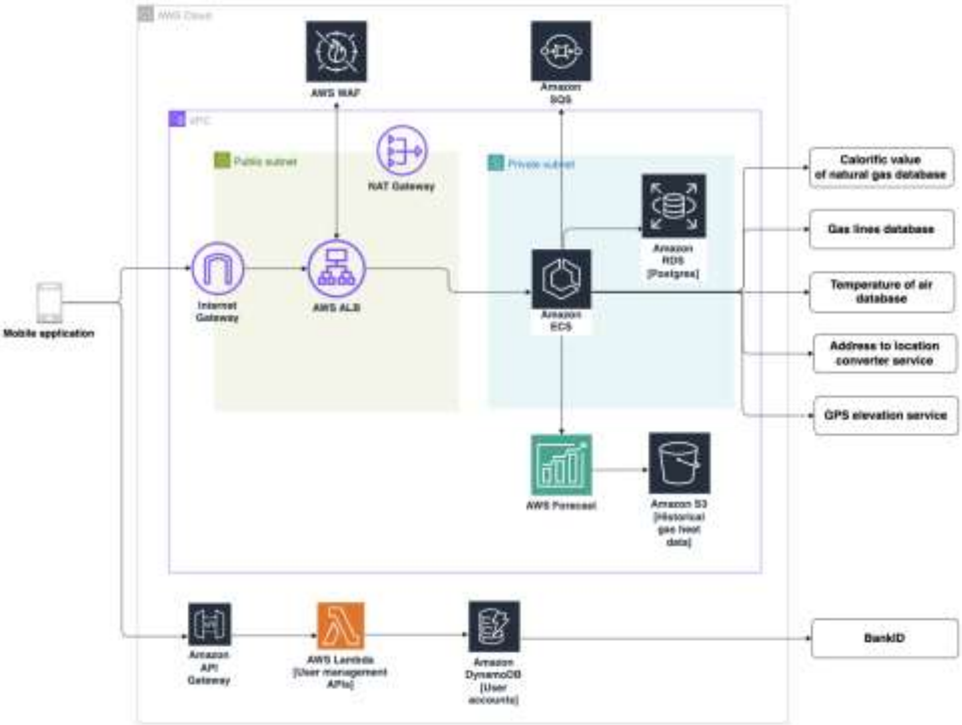

Fig.9. Infrastructure-centric infrastructure architecture model

To represent the application-to-infrastructure level binding it's useful to consider one more viewpoint of the system [10], which represents interactions between the application-level components and infrastructure-level components.

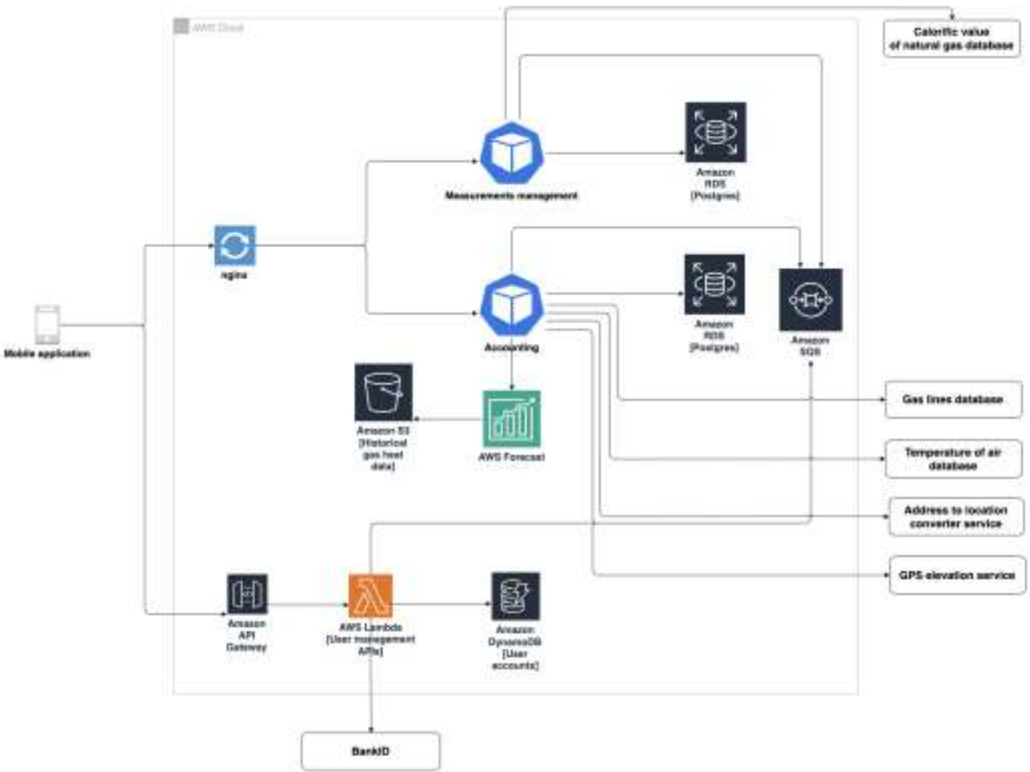

Fig. 10. Application-centric infrastructure architecture model

Conclusions

In the scope of this research, the architectural model of the gas metering automation system based on the innovative concept of virtual point of gas metering, was invented. The architectural model extends the concepts outlined in the conceptual model and considers the most vital aspects of the system architecture: components model, behaviors model, domain data models, external interactions model on the application level, as well as infrastructure-centric and application-centric models on the infrastructural level.

Also, in the scope of architectural model discovery, the problems of gas calorific value predictions, virtual temperature points, and monthly usage calculations were addressed.

Overall, the results of this research outline an architectural model of the automated system of gas metering as well as form a solid foundation for future research into the creation and introduction of the system.

Future research

The future research points which originate from the performed research might include the following:

- Research on the integration of the system into the existing global gas metering ecosystem of Ukraine.
- Research on uniform distribution of usage throughout the period between measurements recording.

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Література

1. Про внесення змін до деяких законів України щодо запровадження на ринку природного газу обліку та розрахунків за обсягом газу в одиницях енергії: Закон України від 02.11.2021 р. № 1850-IX. Відомості Верховної Ради України. 2022. № 5. С. 30.
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