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SOFTWARE COMPONENT DEVELOPMENT FOR PARALLEL GATEWAYS DETECTION AND QUALITY ASSESSMENT IN BPMN MODELS USING FUZZY LOGIC

The quality of business process models is a critical factor in ensuring the correctness, efficiency, and maintainability of information systems. Within the BPMN notation, which is nowadays a standard of business processes modeling, parallel (AND) gateways are of particular importance. Errors in their implementation, such as incorrect synchronization or termination of parallel branches, are common and difficult to detect by traditional metrics such as the Number of Activities (NOA) or Control-Flow Complexity (CFC). In this paper, we propose a method for evaluating the correctness of AND-gateways based on fuzzy logic using Gaussian membership functions. The proposed approach is implemented as a software component that analyzes BPMN models, provided in XML format, identifies all AND-gateways, and extracts structural characteristics, i.e. the numbers of incoming and outgoing sequence flows. This features are evaluated using "soft" modeling rules based on fuzzy membership functions. Additionally, an activation function with the 0.5 threshold is used to generate binary quality indicators and calculate an integral quality assessment measure. The software component is developed using Python, as well as third-party libraries: Pandas, NumPy, and Matplotlib. A set of 3729 BPMN models from the Camunda open source repository was used for experimental calculations. Of these, 1355 models contain 3171 AND-gateways. The obtained results demonstrate that 71.2% of the gateways are correct, and 28.8% have structural violations. In 50% of the models, the quality score is 1.00, which indicates high quality, however minimum values of 0.02 indicate the need for automated verification of business process models. The considered approach allows detecting AND-gateways modeling errors, increasing the reliability of BPMN models and offering the capabilities for intelligent business process modeling support.
Keywords: business process modeling, parallel gateways, quality assessment, fuzzy logic, software component.

Introduction. A business process is defined as a sequence of coordinated tasks or activities performed within an organizational or technical context to achieve specific goals or create value for customers [1].

These processes encompass events, activities, and decision-making steps that support the overall operations of an organization and ensure the delivery of goods and services [2].

Visualization of business processes with the help of graphical diagrams is an effective tool for their understanding, analysis and improvement [3]. High-quality business process models are considered as key assets within the Business Process Management (BPM) life cycle [3]. They allow designing, analyzing, optimizing, and automating the organizational workflows [3].

BPM is an interdisciplinary approach that combines information technology and management practices to identify, model, implement, and monitor business processes [4]. The central element of BPM is process modeling, which provides a graphical representation of activities, events, and decisions in an organization [5].

BPM is aimed at improving the quality of services and efficiency of enterprises by optimizing internal processes [6]. Process modeling serves as a convenient tool for representing the organizational activities in a format suitable for further analysis, making it an important component of BPM [6].

The BPMN (Business Process Model and Notation) provides a set of graphical elements for describing events, actions, gateways, and flows involved in a process. These elements are adapted for both technical and non-technical users [6]. BPMN models use start and end events to indicate the beginning and end of a process, and also include intermediate events and tasks that describe the execution of the process [6].

Process modeling is supported by graphical diagrams and text annotations, which ensures the BPMN models coherence and comprehensibility [7]. This facilitates effective communication between business users and IT professionals responsible for the implementation and maintenance of information systems [7].

State-of-the-art. In the modern BPM practice, special attention is paid to the use of formal notations for describing, documenting, and analyzing business operations. The most common among them are BPMN (Business Process Model and Notation), EPC (Event-driven Process Chain), and IDEF-based notations, in particular IDEF0 and DFD (Data Flow Diagram) [8]. These approaches provide a standardized framework for formalizing processes, which is critical for their further analysis, optimization, and automation.

Among these notations, BPMN has significantly outpaced EPC in recent years in terms of popularity and prevalence in organizations implementing the BPM approach [9]. This is due to the growing flexibility, standardization, and wide support of BPMN in modeling tools.

The BPMN language allows describing workflows as sequences of tasks and events connected by control flows that reflect the logic of actions in the process [10]. This provides an accurate and intuitive view of business processes. BPMN provides for the use of gateways, which play the role of logical branching and merging nodes. Gateways allow modeling parallel, alternative, or inclusive execution of process branches, which is extremely important for complex scenarios [10].

A key advantage of BPMN is the ability to model multi-role processes. This is realized through the concepts of pools and lanes, which define the boundaries of the process and the roles of its participants, respectively [10]. Each pool corresponds to a separate process or organizational unit, while lanes illustrate the distribution of tasks between different performers, which ensures transparency and clarity of the model.

BPMN also supports the display of start, intermediate, and end events that signal the beginning, progress, and completion of a process, respectively [10]. This allows effectively modeling processes in terms of controlling execution and responding to internal or external events.

Fig. 1 demonstrates the set of business process design primitives proposed by BPMN.

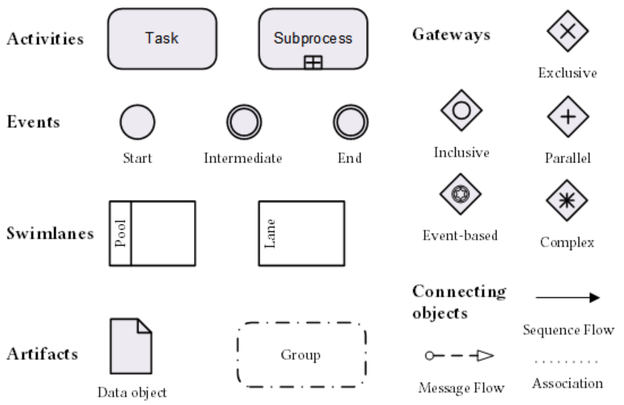

Fig. 1. BPMN design primitives

Thus, BPMN is now the de-facto standard for modeling business processes in many industries due to its accuracy, flexibility, support for complex logic, and convenience for both technical and business users.

The quality of a business process model is a critical factor in its effectiveness in use. Adherence to defined modeling standards and best practices is considered a key indicator of a quality model. For this purpose, specialized frameworks have been developed, such as BPMN modeling guidelines, SEQUAL (SEmiotic QUALity) and other evaluation systems that form the criteria for compliance of business process models with established methodological approaches [11].

One way to assess the quality of BPMN models is to use formal metrics based on the size and structural complexity of the model. These metrics include the number of elements, the length of the longest path between elements, and the analysis of the relationships between them [12]. These metrics allow assessing the architectural complexity of the model, which is important for its perception, analysis, and maintenance.

More specific structural metrics include the Number of Activities (NOA) and the Control-Flow Complexity (CFC) [13].

The NOA metric reflects the total number of actions or tasks within the model, which allows assessing its scale and detail [13]. In turn, CFC determines the level of complexity of the control logic in the process, in particular the number and types of logical branches, such as AND, XOR, and OR gateways [13]. This metric is especially important for identifying potential risks of incorrect execution or difficulty of process automation.

Having standardized metrics and criteria for assessing model quality plays an important role in implementing BPM initiatives. They allow conducting a formal analysis of business process models, identify their weaknesses, and ensure that processes meet organizational and technical requirements. This ensures not only visibility but also interoperability of BPMN models within large information systems.

Problem statement. Despite the widespread use of existing business process quality metrics, such as NOA, CFC, and others, these metrics have limited ability to detect specific modeling errors related to semantic correctness, logical consistency, or violation of notation rules.

In particular, they are not able to capture logical errors such as misuse of gateways, lack of process completion, incorrect transitions between events, etc.

Such deficiencies can reduce the comprehensibility of BPMN models, create difficulties in the implementation or automation of processes, and lead to execution errors despite formally satisfactory metric values.

Therefore, there is a need to expand approaches to business process model quality assessment that would take into account not only structural characteristics but also logical and semantic correctness.

Previous studies have shown that parallel (AND) gateways are among the most erroneous BPMN elements, with an error rate of almost 29%. This indicates that even experienced business analysts often make mistakes when using parallel logic, in particular when synchronizing or terminating a workflow incorrectly.

Thus, detecting incorrect AND-gateways is critical, as errors in their use can lead to incorrect synchronization of parallel branches, which in turn causes failures in the execution of the business process and makes it impossible to automate it.

Materials and methods. The proposed procedure for processing BPMN models in XML format to detect AND-gateways (Fig. 2) consists of four main stages.

1. Load a BPMN file that contains a description of the business process in the form of an XML document.

2. Transform the model is into a directed graph, which identifies all the nodes that correspond to the type of AND gateways.

3. Analyze the obtained XML structure, where AND gateways are identified using "parallelGateway" tags that contain the corresponding inputs and outputs.

4. Extract the key characteristics of each AND gateway, such as the number of input and output threads, which are subsequently used to assess their correctness and identify potential errors in the model.

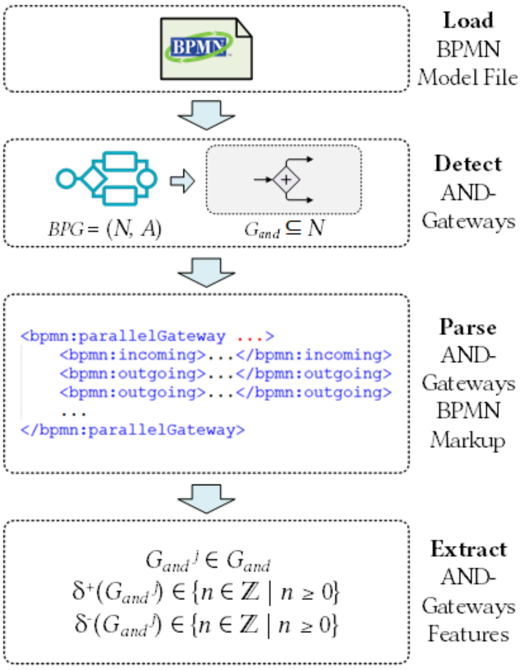

Fig. 2. AND-gateways detection in BPMN models

The BPMN model is interpreted as an oriented process graph:

$$BPG = (N, A), \tag{1}$$

where:

- N – the set of nodes, i.e. business process elements;
- A – the set of arcs, i.e. sequence and message flows.

Within the set N, all nodes corresponding to the type of AND-gateways are detected $G_{and} \subseteq N$.

Structural characteristics are extracted from each AND-gateway, including the number of input and output sequence flows.

The presented approach (Fig. 3) is used to identify and evaluate the correctness of the use of AND-gateways in BPMN business process models.

At the first stage, BPMN files are downloaded and all AND-gateways in the model structure (1) are identified. Then these gateways are converted into feature vectors that describe their structural characteristics, including:

- $\delta^-(G_{and})$ – the number of incoming sequence flows;
- $\delta^+(G_{and})$ – the number of outgoing sequence flows.

The resulting vectors are fed to the fuzzy logic system, which analyzes the compliance of AND-gateways with the established modeling rules:

R1: The split gateway should have one incoming and two outgoing sequence flows:

$$\delta^-(G_{and}) = 1 \wedge \delta^+(G_{and}) = 2 \tag{3}$$

R2: The join gateway should have one incoming and two outgoing sequence flows:

$$\delta^-(G_{and}) = 2 \wedge \delta^+(G_{and}) = 1 \tag{4}$$

In this approach, we propose to use fuzzy logic together with a Gaussian membership function to evaluate the correctness of AND-gateways in BPMN models. This approach is motivated by the fact that traditional evaluation methods are based on rigid rules and structural metrics that do not take into account the uncertainty and variability of real-world modeling.

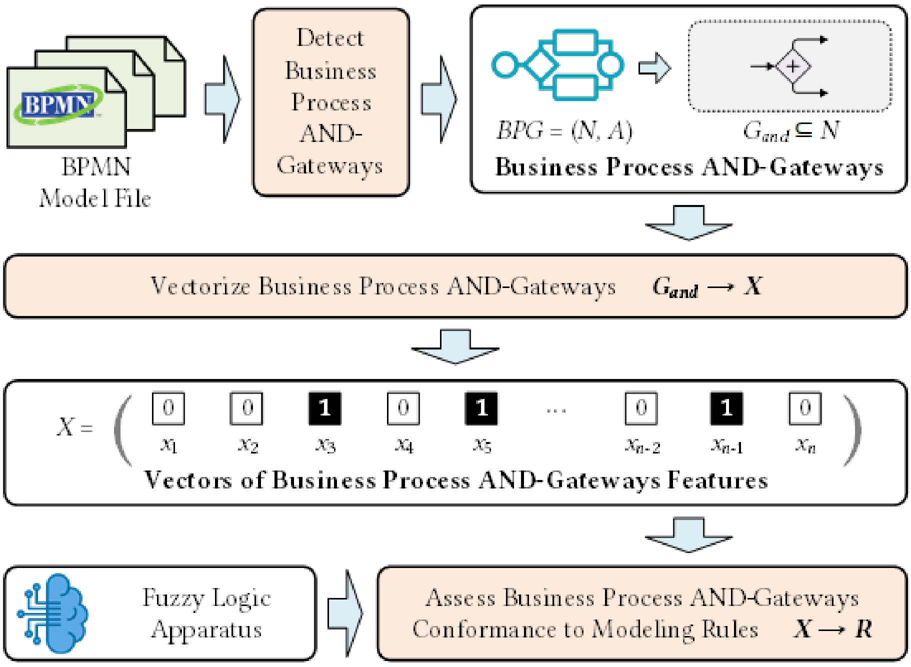

Fig. 3. AND-gateways identification and evaluation approach

Fuzzy logic, unlike binary approaches (3) – (4), allows for flexible interpretation of the degree of compliance of gateways with modeling rules, taking into account intermediate values, not just "correct" or "incorrect".

It is proposed to use the Gaussian membership function:

$$\mu_A(x) = \exp[-(x-\mu)^2 / 2\sigma^2], \quad (5)$$

where:

- μ – the mean, representing the center of the peak;
- σ – the standard deviation, controlling the width of the bell curve.

The Gaussian membership function (5) is particularly effective for this task because it provides a smooth estimate of the deviation of gateway parameters from the normative values, without abrupt transitions [14]. This is important in the context of modeling, where the boundaries between right and wrong can be blurred due to different modeling styles or process complexity.

Thus, the combination of fuzzy logic and the Gaussian function (5) allows for a flexible and interpretable evaluation system (Fig. 4) that is able to take into account the context and provide practical recommendations for model improvement.

The AND logical operation in fuzzy logic is realized by calculating the minimum value between two membership functions. Formally, this is expressed as:

$$\mu_{\text{and}} = \min(\mu_1, \mu_2), \quad (6)$$

where μ_1, μ_2 – the values of membership functions for two fuzzy sets.

This means that the result of membership in the intersection of sets (6) is determined by the lowest degree of membership among the input elements.

The logical operation OR in fuzzy logic is defined as the maximum between the values of the membership functions of the corresponding fuzzy sets:

$$\mu_{\text{or}} = \min(\mu_1, \mu_2), \quad (7)$$

where μ_1, μ_2 – the values of membership functions for two fuzzy sets.

In this case, the result reflects the highest degree of membership in at least one of the sets (7), which is consistent with the logic of union in classical Boolean algebra.

At the final stage, the system generates an assessment of the correctness of each gateway based on the specified activation function.

An activation function L with a binary output is defined as equal to 1 if the value of the membership function μ is at least 0.5, and 0 if it is less than 0.5, i.e. $L \in \{0, 1\}$ depending on the threshold value μ.

The following expression defines an integral assessment of the quality of using AND-gateways in a BPMN model:

$$Q(G_{\text{and}}) = (\Sigma_{i \in N} L_i) / |G_{\text{and}}|, \quad (8)$$

where L_i is a binary value (0 or 1) that reflects the correctness of each AND-gateway.

Results and discussion. The proposed algorithm (Fig. 5) provides an automated assessment of the quality of using AND-gateways in BPMN models based on fuzzy logic.

The process begins with a step-by-step reading of BPMN files.

For each file, the system detects all AND-gateways, and then parses the XML markup to extract the corresponding elements.

Next, the structural features of each gateway are extracted, such as the number of incoming and outgoing threads.

These characteristics are sent to the fuzzy logic module, which validates the gateways according to the specified modeling rules.

Based on the results, the quality level of each gateway is calculated.

After processing all the BPMN files, the system proceeds to the final stage, where a generalized report on

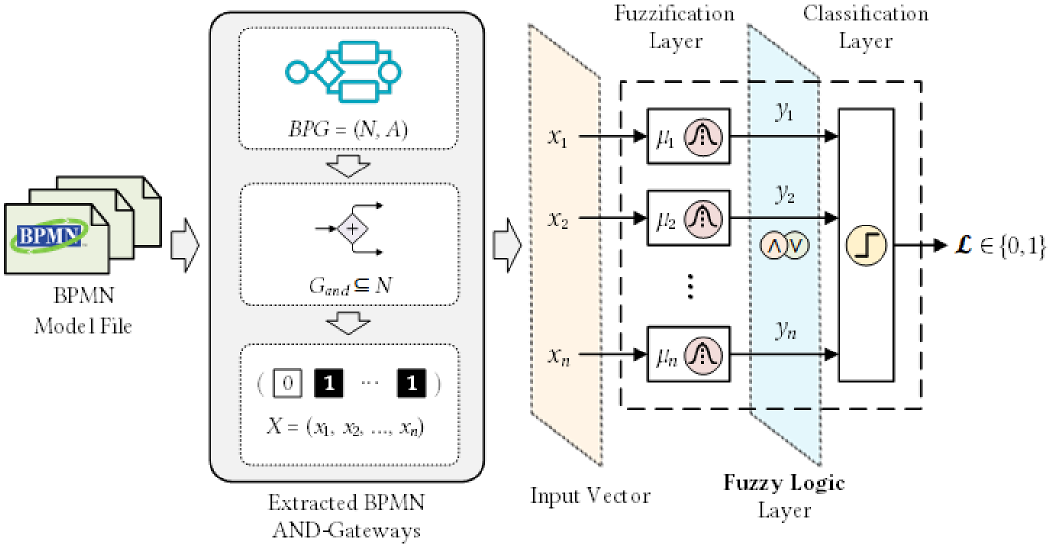

Fig. 4. AND-gateways evaluation system based on fuzzy logic

the quality of the use of AND gateways in the analyzed models is generated.

This approach allows systematically identifying common modeling errors and improve the quality of business processes.

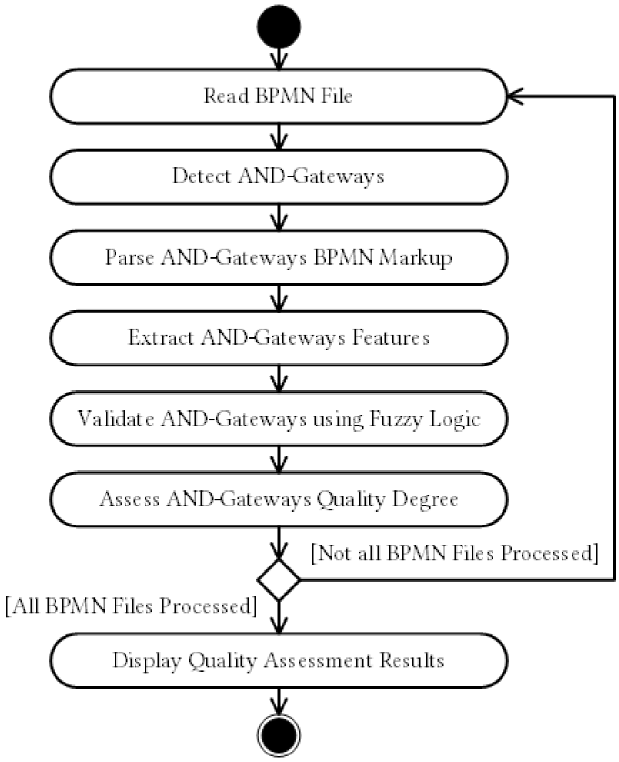

Fig. 5. AND-gateways quality assessment algorithm

The proposed algorithm is implemented using the Python programming language, which provides flexibility and efficiency in processing BPMN models in XML format.

The Pandas and NumPy libraries were used to read, analyze, and process data, which allow working with tabular structures and performing mathematical operations on sets of AND gate characteristics.

The visualization of the quality assessment results is implemented using the Matplotlib library, which made it possible to create graphs and charts to represent the degree of gateway compliance with the modeling rules.

The chosen technological platform allowed for high scalability, repeatability, and convenience of the experiments within the study.

The experiments are performed with the large set of 3729 BPMN models, available for free in the Camunda GitHub repository [15]. Out of this set of BPMN models, 1355 contain AND-gateways. There were detected 3171 AND-gateways that were further analyzed.

Based on the dataset [15], the following Gaussian membership function parameters were calculated:

- the mean, $\mu = 0.78$;
- the standard deviation, $\sigma = 0.72$.

Fig. 6 demonstrates the distribution of incoming and outgoing sequence flows for AND-gateways in BPMN models.

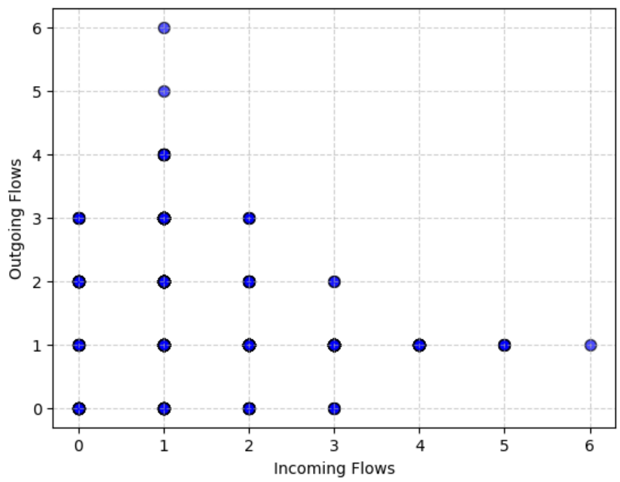

Fig. 6. AND-gateways incoming and outgoing flows distribution

Each point on the chart (Fig. 6) represents one gateway, where the X-axis coordinate indicates the number of incoming flows and the Y-axis coordinate indicates the number of outgoing flows.

It can be observed that most gateways have 1 or 2 inputs with 1-3 outputs, which corresponds to the typical use of AND gateways to start or synchronize parallel branches.

There are also isolated cases with 4-6 input or output streams, which may indicate complex logic designs or potentially erroneous modeling.

The charts below (Fig. 7 – 10) outline Gaussian membership functions used to evaluate the correctness of incoming and outgoing flows of AND-gateways.

The number of sequence flows is plotted on the X-axis, and the degree of membership is plotted on the Y-axis, showing how well the corresponding value matches the corresponding modeling rule. The degrees of membership decrease sharply when deviating from the peak value, which allows quantifying the degree to which the gateway structure is correct.

Fig. 7 demonstrates the obtained membership function used to assess AND-split gateways incoming flows.

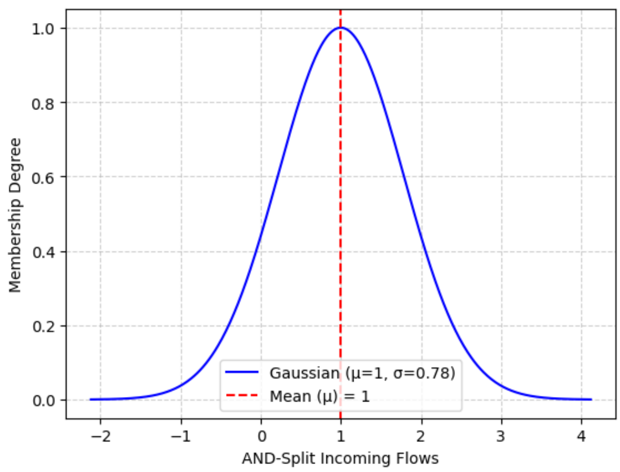

Fig. 7. Membership function to assess AND-split gateways incoming flows

The graph (Fig. 7) shows that the function reaches a maximum (μ = 1.00) with one incoming flow, which is indicated by the vertical dashed red line. This indicates that the expected value for the AND-split gateway is one incoming flow, according to BPMN modeling rules.

Fig. 8 demonstrates the obtained membership function used to assess AND-split gateways outgoing flows.

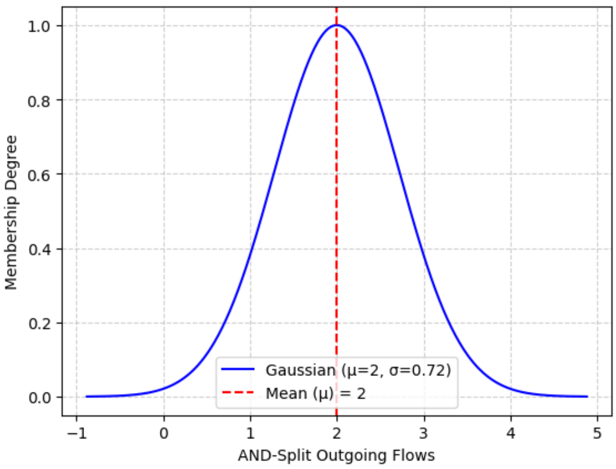

Fig. 8. Membership function to assess AND-split gateways outgoing flows

The graph (Fig. 8) shows that the function reaches a maximum (μ = 1.00) with two outgoing flows, which is indicated by the vertical dashed red line. This indicates that the expected value for the AND-split gateway is two outgoing flows, according to BPMN modeling rules.

Fig. 9 demonstrates the obtained membership function used to assess AND-join gateways incoming flows.

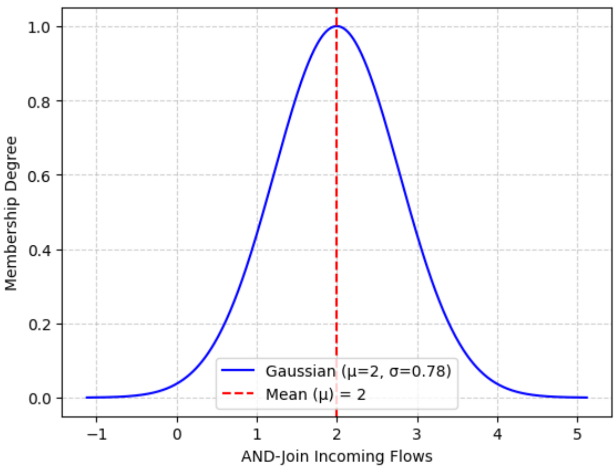

Fig. 9. Membership function to assess AND-join gateways incoming flows

The graph (Fig. 9) shows that the function reaches a maximum (μ = 1.00) with two incoming flows, which is indicated by the vertical dashed red line. This indicates that the expected value for the AND-join gateway is two incoming flows, according to BPMN modeling rules.

Fig. 10 demonstrates the obtained membership function used to assess AND-join gateways outgoing flows.

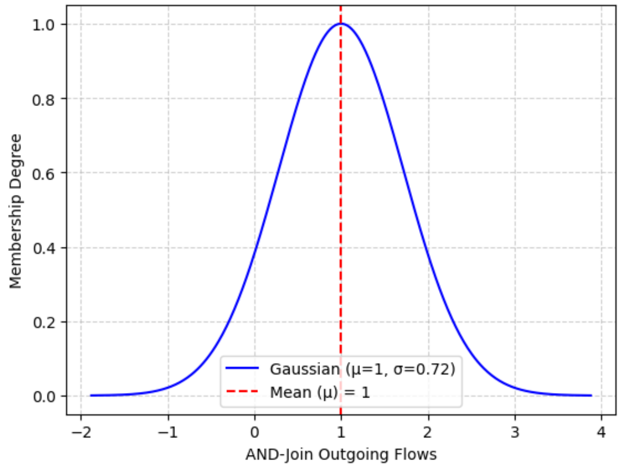

Fig. 10. Membership function to assess AND-join gateways outgoing flows

The graph (Fig. 10) shows that the function reaches a maximum (μ = 1.00) with one outgoing flow, which is indicated by the vertical dashed red line. This indicates that the expected value for the AND-join gateway is one outgoing flow, according to BPMN modeling rules.

Among the total number of 3171 identified AND-gateways, 2257 (71.2%) are detected as correct, while 914 (28.8%) are detected as incorrect (Fig. 11).

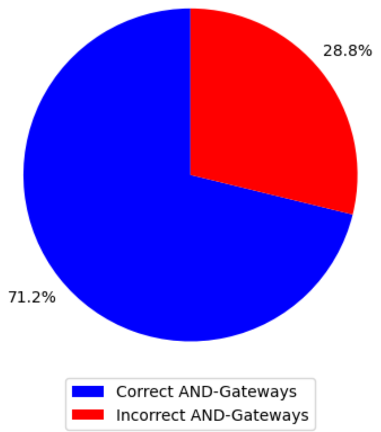

Fig. 11. Detected correct and incorrect AND-gateways

The quality (8) assessment results obtained for 1355 analyzed BPMN models, containing AND-gateways, are the following:

- mean value of 0.85 indicates a generally high level of quality of the use of AND-gateways in the considered business process models;
- the standard deviation of 0.21 indicates a moderate variability of quality values, which means that there are both high-quality and lower-quality implementations of AND-gateways;
- the minimum value of 0.02 demonstrates the presence of single models with an extremely low quality score, which may indicate critical errors or incorrect use of AND-gateways;
- the first quartile (25%) of 0.72 means that at least a quarter of the models have a quality value below 0.72, which may require additional analysis or improvement;

- the median (50%) of 1.00 shows that at least half of the models reach the highest possible quality value, which indicates a general trend toward correct design of AND-gateways;
- the third quartile (75%) of 1.00 emphasizes that 75% of the models have a quality score of 1.00 or less, which further confirms the high overall quality;
- the maximum value of 1.00 indicates that some models implement AND-gateways flawlessly in terms of the selected quality criterion.

Conclusion and future work. This study proposed an approach to assessing the quality of parallel (AND) gateways in BPMN business process models using fuzzy logic and the Gaussian membership function.

It is noted that traditional structural metrics, such as NOA, CFC, and others are not able to detect logical and semantic errors associated with the incorrect use of gateways.

The proposed approach allows not only to quantify the compliance of the structural characteristics of gateways with the established modeling rules, but also to flexibly interpret the degree of their correctness under conditions of uncertainty.

Using the implementation of the algorithm in Python and the Pandas, NumPy, and Matplotlib libraries, efficient processing of a large set of BPMN models is completed.

The analysis of 1355 models containing 3171 AND-gateways demonstrated that 71.2% of BPMN models comply with the modeling rules, and 28.8% were identified as potentially erroneous.

The average quality level is 0.85, which indicates a relatively high quality of AND-gateways, although the presence of some models with critically low values (i.e., 0.02) indicates the need for more thorough BPMN models control and validation.

Thus, the developed approach provides an automated, scalable, and interpretable assessment of the correct use of parallel gateways in BPMN models, which is an important step towards improving the reliability and efficiency of business processes in the context of digital transformation of enterprises.

In the future work, the developed software component will be integrated with the comprehensive intelligent information technology for quality assessment of BPMN models. It is also planned to apply fuzzy logic-based approach to other business process elements to detect incorrect structures and provide recommendations for their improvement.

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РОЗРОБКА ПРОГРАМНОГО КОМПОНЕНТУ ДЛЯ ВИЯВЛЕННЯ ТА ОЦІНЮВАННЯ ЯКОСТІ ПАРАЛЕЛЬНИХ ШЛЮЗІВ У МОДЕЛЯХ BPMN НА ОСНОВІ НЕЧІТКОЇ ЛОГІКИ

Якість моделей бізнес-процесів є критично важливим фактором для забезпечення коректності, ефективності та підтримуваності інформаційних систем. У нотації BPMN, яка сьогодні є стандартом моделювання бізнес-процесів, особливе значення мають паралельні (AND) шлюзи. Помилки в їх реалізації, такі як неправильна синхронізація або завершення роботи паралельних гілок процесу, є поширеними і їх важко виявити за допомогою традиційних метрик, таких як Number of Activities (NOA) або Control-Flow Complexity (CFC). У цій статті пропонується метод оцінки коректності роботи AND-шлюзів на основі нечіткої логіки з використанням функцій приналежності Гаусса. Запропонований підхід реалізовано у вигляді програмного компонента, який аналізує BPMN-моделі, надані у форматі XML, ідентифікує всі AND-шлюзи та виокремлює структурні характеристики, тобто кількість вхідних та вихідних потоків послідовностей. Ці характеристики оцінюються за допомогою «м'яких» правил моделювання, заснованих на нечітких функціях належності. Додатково використовується функція активації з порогом 0,5 для формування бінарних показників якості та обчислення інтегральної оцінки якості. Програмний компонент розроблено з використанням мови Python, а також сторонніх бібліотек: Pandas, NumPy та Matplotlib. Для експериментальних розрахунків використано набір з 3729 BPMN-моделей з відкритого репозиторію Camunda. З них 1355 моделей містять 3171 AND-шлюз. Отримані результати демонструють, що 71,2% шлюзів є коректними, а 28,8% мають структурні порушення. У 50% моделей оцінка якості дорівнює 1,00, що свідчить про високу якість, проте мінімальні значення 0,02 вказують на необхідність автоматизованої верифікації моделей бізнес-процесів. Розглянутий підхід дозволяє виявити помилки моделювання AND-шлюзів, підвищити надійність BPMN-моделей та надати можливості для інтелектуальної підтримки моделювання бізнес-процесів.

Ключові слова: моделювання бізнес-процесів, паралельні шлюзи, оцінка якості, нечітка логіка, програмний компонент.

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