Assessing interoperability assessment

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Efficient integrated systems depend on strong interoperability, which is a non-functional requirement for heterogeneous systems. Objective measurement is essential for assessing a system's adherence to interoperability norms. This paper conducts a systematic literature review to identify methods for objectively measuring interoperability. The review uncovers the presence of well-established, subjective methods. Consequently, the paper proposes integrating objective measurements into a standardized model to improve interoperability measurement across various sectors and systems. The proposed integration approach seeks to replace a collection of opinion-based questionnaires with a unified standardized method for objectively measuring interoperability.

Additional Key Words and Phrases: interoperability, semantic, organizational, measuring, methods, metrics, maturity model, framework

1 INTRODUCTION

Interoperability refers to the degree to which two or more systems, products or components can exchange information and use the information that has been exchanged [1]. Essentially, interoperability involves enabling the seamless collaboration of two software pieces. It allows for the integration of various applications across different domains of software systems. There are four main layers of interoperability. Legal, organisational, semantic, technical [2]. The technical layer enables data exchange between different systems. This layer focuses on protocols, data formats, and APIs. Achieving data exchange by means of these technologies forges the foundation of interoperability. The semantic interoperability layer builds on top of the technical layer and focuses on a shared understanding of data between systems. This layer preserves the compatibility and meaning of the exchanged data. These two layers combined facilitate data exchange while preserving the understanding of the data and its context. Allowing systems to correctly interpret and process the data they receive. The organizational layer does not concern technicalities. Instead it focuses on the processes of systems that collaborate. Thus, the focus lies on the organizational aspects for achieving interoperability between the systems of different institutions or organizations. Aligning business processes and managing the change in structure within the organization are examples of what is handled in the organizational layer of interoperability. The topmost layer of interoperability is the legal layer. The organizational layer addresses how different institutions or organizations intend to share their data and information. The legal layer governs what can be shared and under what conditions. Therefore, it covers essential topics such as privacy, cybersecurity, and intellectual property rights, while also ensuring the presence of contracts to monitor the interoperability procedure.

Table 1 shows the interoperability layers.

Table 1. Interoperability Layers

Layer	**Description**
Legal	Ensure regulatory compliant data exchange
Organisational	*Enable effective collaboration*
Semantic	*Meaningful data exchange*
Technical	Facilitate data exchange

Assessing the performance of interoperability between systems is crucial since multiple sectors rely on it. The following paragraphs illustrate the importance interoperability for some sectors.

The absence of a well-established reference standard for the Internet of Things (IoT) platform poses significant challenges for the technology. [3]. IoT has to cope with a high degree of heterogeneity at many levels, under which data/semantic interoperability [4, 5].

The healthcare sector is developing technologies to enable controlled access to software systems. Enabling easy access to patient records, reduced healthcare costs, and minimizing healthcare errors [6]. Multiple attempts have been made to leverage the benefits [7–10]. Current interoperability challenges in healthcare are standardization problems, incompatible clinical ontologies, and a resistance to change [6].

A range of factors associated with interoperability serve as key indicators of citizens' intention to use an e-government service. Therefore, governments have a major interest in interoperability. These key indicators are perceived ease of use, compatibility and trustworthiness [11]. Enhancing interoperability among public services will contribute to the improvement of these factors, leading to an increased intention of citizens to use e-government services. A wide range of maturity models exist for analyzing interoperability in e-government. These models aim to enhance public services into a set of systems with a high level of maturity in interoperability [12–14].

Technologies throughout sectors rely on interoperability and as a result, well-defined layers of interoperability have been established [2]. These layers are present in questionnaire based assessment models used to measure interoperability quantitatively. However, it seems that interoperability becomes hard to measure when a quantitative approach is taken. This paper analyzes the current methods and metrics for assessing semantic and organizational interoperability and aims to define directions for interoperability measurement of the future.

1.1 Research Question

Interoperability is in high demand across many sectors. Despite the availability of qualitative models to assess the level of interoperability, both existing challenges and emerging ones continue to

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persist. It can not yet be stated that these challenges exist because of incomplete methods. This literature review will reveal where existing methods satisfy requirements. The goal is to analyze the methods and metrics for measuring interoperability to find gaps and provide directions for solutions. We aim to achieve this goal by answering the following research question:

"To what extent do the current methods and metrics measure interoperability?"

The following sub questions help to answer this question:

(1) What are the current methods and metrics for measuring interoperability?
(2) Where do the methods and metrics for measuring interoperability come short?
(3) What are promising future directions for measuring interoperability?

2 METHODS

2.1 Key Words and Search Query

This paper conducts a systematic literature review of metrics and methods to measure semantic and organizational interoperability. A set of key words is formed to execute the literature review.

The terms "method" and "metric" as well as "organizational interoperability" and "semantic interoperability" are all derived from the research question. These keywords serve as the base for identifying relevant literature.

The European Commission has published the CAMSS Assessment EIF Scenario [15] in conjunction with the interoperability layers [2], which serves as a framework for evaluating the standards and specifications utilized. To discover articles that suggest novel approaches for evaluating interoperability, the search terms include the keyword "assess*". The title of the CAMSS Assessment EIF Scenario [15] publication suggests that it is a model for evaluating or assessing the interoperability standards and specifications. Therefore, by including the term "assess*" in the search, it is more likely to yield articles that propose innovative models or methods for evaluating interoperability.

Assessments like the CAMSS Assessment often use surveys. The literature review must contain methods that measure interoperability by calculating scores based on models or characteristics. The search term "measure*" is therefore included in the key words.

There are no equivalent terms or synonyms used for interoperability in the search query. Interoperability is the industry standard term [1]. Interoperability is a required term in the search query. Additionally, it is important to consider the layers of interoperability [2]. The scope of this research concerns the semantic and organizational layers. The search query contains a limitation by requiring at least one of the layers to be in the results.

The collected key words and limitations form the search query:

(Metric|method|assess|measuring|measure*|maturity) AND (semantic|organizational|organisational) AND interoperability*

2.2 Article Identification

In order to capture as many relevant articles as possible, a wide range of databases were searched for articles related to metrics and/or methods for measuring semantic and organizational interoperability. The databases and their access points are listed in Table 2.

Table 2. Databases

Database	URL
Research Gate	https://www.researchgate.net/search
Scopus	https://www.scopus.com/
Semantic Scholar	https://www.semanticscholar.org/
Science Direct	https://www.sciencedirect.com/
Web of Science	https://www.webofknowledge.com/
IEEE Xplore	https://ieeexplore.ieee.org/

Executing the search query on the Research Gate and Web of Science database requires adjustments to the search query. The adjusted query is:

(Metric OR method OR assess OR measuring OR measure* OR maturity) AND (semantic OR organizational OR organisational) AND interoperability*

Science Direct lacks support for the asterisk(*) symbol. The query has to be executed without the asterisk symbols.

(1) Research Gate - 100
(2) Scopus - 3277
(3) Semantic Scholar - 13600
(4) Science Direct - 30191
(5) Web of Science - 2027
(6) IEEE Xplore - 619

As of May 3rd, 2023, the query across all databases yields a total of 49814 articles.

2.3 Article Quality Assessment

To find relevant articles of sufficient quality a set of inclusion/exclusion criteria have been constructed. The first criteria is that the article has to provide information about a metric and/or method for measuring interoperability. The search query has been constructed in a way that it allows for synonyms of words, but is limited to yielding results that include the three important components (or their synonyms) of the query. While the articles are searched through in order of the relevance metric of the databases, any results that do not discuss information about a metric and/or method for measuring interoperability are not included. To ensure the inclusion of relevant papers, a thorough assessment was conducted by reading the abstracts. Papers were retained if their abstracts described a metric and/or method related to measuring interoperability. Any papers that did not meet this criterion were excluded from further consideration. This approach helped to refine the selection process and focus on articles directly aligned with the research objective. The results from each database were analyzed in chronological order of their relevance index. When ten consecutive papers did not meet the specified criterion in the abstract, the remaining papers of that database were discarded from further consideration. This approach ensured that, within regards to a limited time frame, only the most relevant papers aligned with the research objective were retained for further analysis.

The metrics and methods identified in the articles cannot be limited to a specific domain. They must be universal enough to be applicable across multiple domains.

Table 3. Summary of search results

Database	Results	Relevant	Duplicate
Semantic Scholar	13600	4	-
Scopus	3277	4	4
IEEE Xplore	619	3	-
Research Gate	100	8	-
Web of Science	2027	0	-
Science Direct	30191	4	1

The examination of search results from the databases and the application of inclusion/exclusion criteria identify a total of 23 relevant articles. Table 3 provides a summary of the search results, with the "Relevant" column indicating the number of articles meeting the inclusion/exclusion criteria and the "Duplicates" column showing the number of articles in the database that are relevant but excluded due to duplication. Appendix A: Table 6 presents the selected articles, categorized based on their distinction between organizational and semantic interoperability. Additionally, a context is provided to indicate the specific domain of each article.

3 ARTICLE ANALYSIS

3.1 A String Metric for Ontology Alignment

Stoilos et al. provide an improved string-distance metric for semantic interoperability measurement. The string metric helps to improve the semi-automated process of aligning ontologies. An ontology is the description of knowledge in the form of a set of concepts, their properties, and their relationships within a domain.

The concepts represent the entities, known as classes of objects within a domain. Relationships illustrate the connections between the concepts. Properties describe attributes of the concepts. Stoilos et al. [16] propose a string-distance metric that is specifically designed to compare class and property names of an API. In software systems that utilize APIs, the design model often consists of the corresponding class diagram of the domain. These class diagrams, which are similar to ontologies, encompass elements such as classes, properties, and relationships. Hence, the resulting API reflects the functional implementation of the domain's ontology. The approach introduced by Stoilos et al. utilizes the API interface to extract these class and property names and assesses the degree of alignment with an ontology. In their work, Stoilos et al. [16] distinguish themselves from other methods for finding similarities between ontologies, such as Anchor-PROMPT [17], QOM [18], and Cupid [19]. They achieve this differentiation by paying special attention to each characteristic of the ontology alignment process, resulting in a string-distance metric with excellent performance [16]. According to Stoilos et al. [16], a good string metric for measuring semantic interoperability must be fast, stable, intelligent, and discriminating.

1. **Fast**: Since ontologies are used in applications that process data in real-time, the string metric must be computed quickly. As a result, the calculation complexity must be low to enable a fast matching process.

2. **Stable**: Ontology alignment algorithms rely heavily on a threshold, which is a predefined value used to determine the level of similarity between two strings. The threshold serves as a boundary that determines whether the score is sufficient for a match or does not meet the level of acceptance. The string matching algorithm must be stable that even if the algorithm does not have precisely the right threshold, it still performs with good results. This is better than an unstable algorithm that loses its accuracy upon a sudden change in threshold.

3. **Intelligent**: It is crucial for the metric to accurately distinguish between similar words and produce correct results. For instance, some words may be spelled similarly but represent entirely different concepts, such as "cell" and "sell." The metric must identify that words like these are not very similar, although they only differ by one letter.

4. **Discriminating**: When trying to match two sets of words, it's important that each word in the set only matches with one word in the other set. If a word in the first set matches with multiple words in the second set, it can be hard to figure out which match is the best one. So, we need a way to give each match a unique score to avoid this problem. Therefore, the algorithm should generate results that do not often yield the same score. It should give different scores for comparing a single string to multiple other strings.

These requirements are used to forge the string metric specifically for ontology matching.

$$Simm(s1, s2) = Comm(s1, s2) - Diff(s1, s2) + winkler(s1, s2) \quad (1)$$

In the equation, $Comm(s1, s2)$ stands for the commonality, which measures how similar the strings are. $Diff(s1, s2)$ stands for the difference of the strings. The final element is the $winkler(s1, s2)$, which denotes the metric defined by Winkler [20]. The Jaro-Winkler method is a string similarity metric. It extends the Jaro distance algorithm [21] by incorporating a prefix scale factor that gives more weight to the common prefix of the strings. The resulting Jaro-Winkler similarity score ranges from 0 to 1, with 1 indicating a perfect match and 0 indicating no similarity.

The formula for commonality is defined below.

$$Comm(s1, s2) = \frac{2 \cdot \sum_i length(maxComSubString_i)}{length(s1) + length(s2)} \quad (2)$$

The function calculates the largest common substring between the two strings. It is optimized to identify the common substring, remove it from the original strings, and then repeat the process until a longer substring cannot be found. The lengths of the longest substrings are then summed up and divided by the sum of the length of the two original strings. This function is optimized to more accurately identify similarities and measure semantic compatibility, making it an intelligent metric.

The difference between two strings is determined by the length of the unmatched portions of strings from the previous step, using the Hamacher product formula [22]. Stoilos et al. argue that this difference should play a less significant role in determining similarity. The parameters $uLen_{s1}$ and $uLen_{s2}$ represent the length of the leftover unmatched portions of strings, which are scaled with the length of the original strings $s1$ and $s2$. The parameter p can be adjusted to control the importance of the difference in the calculation. Stoilos et al. achieved excellent results with a value of 0.6 for p [16].

$$Diff(s1, s2) = \frac{uLen_{s1} \cdot uLen_{s2}}{p + (1-p) \cdot (uLen_{s1} + uLen_{s2} - uLen_{s1} \cdot uLen_{s2})} \quad (3)$$

3.2 Measuring Similarity between Semantic Business Process Models

Enterprises have their own unique ways of describing and modeling their business processes, using various modelling languages. Examples are Petri nets [23], BPMN [24], and BPEL [25]. When enterprises aim to connect their business processes, a significant amount of manual effort is required to prevent misunderstandings. This task also requires a deep understanding of the business processes and expertise in the field of business process engineering. To address this challenge, Ehrig et al. have developed a model that enables statistical analysis of business processes to discover the degree of interoperability of business processes and their composition.

According to the paper by Ehrig et al. [26], automating the process of discovering appropriate composable business process models can speed up the process. Their approach involves (semi-)automatically identifying synonyms and homonyms of business processes to enable interoperability between different business process models.

Naturally, the more similar the models are, the higher the similarity score will be. Additionally, the use of synonyms within the models has a positive correlation with the similarity score. Therefore, the more synonyms that are used, the higher the similarity score will be. Conversely, the use of homonyms has a negative correlation with the similarity of the business process models.

The paper uses a total of three similarity measures to define the degree of similarity. This is done by calculating the degree of similarity between a pair of process element names (sim_e) and business process models (sim_t) on the levels of syntactic-, linguistic-, and structural measures.

1. **Syntactic**: The amount of common characters in the element names.
2. **Linguistic**: The resemblance of two business process names based on synonyms. Uses a dictionary of synonyms to find the degree of similarity.
3. **Structural**: Compares business process elements in regards to the context in which the processes are situated.

The syntactic and linguistic measures do not take into account the context in which the processes are present. These measures do not consider the surrounding environment or other processes. Structural similarity measures, on the other hand, do take these factors into account. As the name suggests, these measures consider the structure of the processes in the model.

The measures for similarity fulfill the properties *symmetry* and *reflexivity*. For a similarity measure denoted as sim and considering two Semantic Business Process Models (SBPMs) represented by x and y, the measure exhibits symmetry if $sim(x, y) = sim(y, x)$. Additionally, the property of reflexivity is achieved when $sim(x, x) = 1$, indicating that the similarity measure assigns a maximum similarity value when comparing a SBPM to itself.

The measure for syntactic similarity is based on the edit distance measure developed by Maedche and Staab in 2002 [27]. This measure returns a value between 0 and 1. The higher the number, the higher the similarity. A score of 1 represents a perfect match between two strings. This measure is reflected in equation 4 using the variable ed. In summary, equation 4 calculates a similarity score between two strings, c1 and c2, by comparing their lengths and the result of the ed function. It penalizes dissimilarity by subtracting the output of ed from the minimum length value and then squaring the result. The max function ensures that the similarity score is always non-negative by taking the maximum between 0 and the expression inside the parentheses.

$$sim_{syn}(c1, c2) := max(0, \frac{min(|c1|, |c2|) - ed(c1, c2)}{min(|c1|, |c2|)})^2 \quad (4)$$

The measure for linguistic similarity is more complex than the measure for syntactic similarity. Business process models can vary significantly between modelers and from one model to another. To calculate the similarity, the approach considers how similar the process names are based on their linguistic similarity. The process of defining the linguistic similarity is as follows:

1. Identify names of processes that do not have a sim_{syn} of 1. (Not the same strings)
2. Query synonyms for the process name.

WordNet [28] contains all the terms in a synonym relationship. The collection of synonyms of both process names are analyzed for similarities.

3. Find linguistic relationships in process names between models.

When there are no similarities between the sets of synonyms of the business processes, the result of the linguistic formula is 0. If there are similarities present, the linguistic similarity is calculated by equation 5.

$$sim_{ling}(c1, c2) = \frac{1}{max(|n(c1)|, |n(c2)|)} \quad (5)$$

The variables $|n(c1)|$ and $|n(c2)|$ represent the number of synonyms for the first and second process names, respectively. In order for the formula to return a perfect score of 1, $c1$ must be the only synonym for $c2$, and $c2$ must be the only synonym for $c1$.

The similarity degree returned by this linguistic similarity degree differs from the similarity degree returned by the syntactic similarity measure.

The structural similarity measure has two inputs. Just like the other similarity measures these are $c1$ and $c2$. In contrast to the other measures, the structural similarity measures takes context into account.

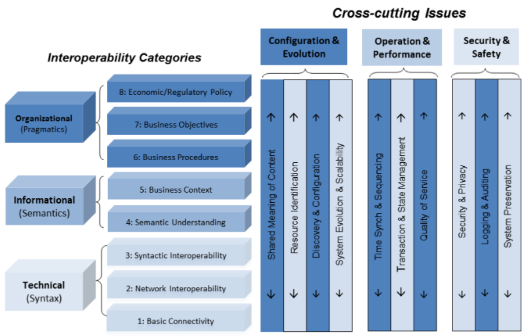

Fig. 1. Extension of GWAC Interoperability Context-Setting Framework for the IMM [29]

3.3 MR Knight - Interoperability Maturity Model

Knight et al. [29] aims to promote a common understanding of the meaning and characteristics of interoperability [29]. To measure the state of interoperability in specific technology deployment domains, Knight et al. identify the key characteristics of interoperability. This is achieved through the development of an interoperability maturity model (IMM), which encompasses a comprehensive list of 33 interoperability criteria organized into six distinct categories. This research focuses on two of the six categories in the interoperability maturity model. These categories, organizational and informational (semantics), are on the left side of Figure 1.

The interoperability maturity model (IMM) includes a section that explains the classification of the state of interoperability into distinct levels of maturity. The classification is performed on the evaluation criteria [29]. The relevant criteria can be found in Table 4.

Table 4. Interoperability Maturity Criteria

ID	Description	Category
17	Compatible business processes and procedures exist across interface boundaries.	Organizational
18	Where an interface is used to conduct business within a jurisdiction or across different jurisdictions, it complies with all required technical, economic, and regulatory policies.	Organizational
19	Information models relevant for data exchanged across the interface are formally defined using standard information modeling languages.	Informational
20	Data exchange relevant to the business context is derived from the information model.	Informational
21	Where the data exchanged derive from multiple information models, the capability to link data from the different information models is supported.	Informational

Assessing the maturity level for each criterion allows the identification of the categories that require improvement to enhance interoperability. This enables organizations to determine whether improvements are needed in organizational and/or semantic interoperability. The interoperability maturity model (IMM) offers guidelines on using the criteria to assess the level of interoperability. The relevant levels for assessing the criteria can be found in Table 5.

Table 5. IMM levels

Level	Meaning
5	*Optimized* – The ecosystem engages in continuous improvement of the process itself.
4	*Planned* – The ecosystem has plans in place for future refinements.
3	*Defined* – The process for defining compatible interface messages assures that business processes and procedures on either side of the interface are compatible.
2	*Managed* – Incompatibilities in the business processes and procedures across the interface boundaries are managed on a per implementation basis.
1	*Initial* – Ad hoc and chaotic.

These levels are used by the IMM to assess the current level of maturity in interoperability categories, to track the progress of the categories and to set goals for the categories as well. The categories consist out of the layers organizational, informational (semantic), and technical interoperability, along with the cross-cutting issues [29] Configuration & Evolution, Safety & Security, and Operation & Performance. These categories provide a comprehensive framework for assessing and evaluating the maturity levels of interoperability. Shown in Figure 1.

3.4 Assessment of organizational interoperability in e-Government

Margariti et al. [30] introduce a new model and tool for assessing the level of maturity in achieving interoperability. The paper highlights interoperability maturity models commonly referred to in literature.

(1) Levels of Information Systems [31]
(2) Organisational Interoperability Model [32]
(3) Levels of Conceptual Interoperability Model [33]
(4) Enterprise Interoperability Maturity Model [34]

Margariti et al. state that recent researches attempt to clarify and re-conceptualize the layer of organizational interoperability [30]. The research attempts state that there is a need for redefining organizational interoperability. Redefining the definition to "business process interoperability", which refers to the degree of interoperability among the business processes that require alignment. Focusing on the business processes, rather than aspects like inter-organizational agreements and policies.

To get past the challenges of information, Margariti et al. mention that assessment of the degree of organizational interoperability is necessary. A new model and tool to assess the organizational layer of interoperability is presented. This model serves as an extension of existing models, featuring additional criteria that are categorized to emphasize organizational interoperability. Criteria like Table 4. This model is designed to support the advancement of interoperability in e-governments, specifically aligning with the Digital Single Market Strategy for Europe and the EU e-Government Action Plan 2016-2020 [35]. Its purpose is to provide a framework that aids in the development and implementation of interoperability initiatives within the context of public services, facilitating seamless and efficient digital services across European countries.

3.5 Measuring Enterprise Application Software Interoperability Capability

Valatavičius and Gudas [36] measure the interoperability of enterprise application software by executing a detailed computational analysis of web service properties within enterprise architecture software [36]. The researchers used a set of edit distance formulas (Levenshtein, Jaro-Winkler, Jaccard, and Longest Common Subsequence). The Levenshtein edit distance formula calculates the minimum number of operations required to transform one string into another. An operation is either an insertion, deletion, or substitution of a single character. This formula uses recursion to determine the optimal solution for finding the minimum number of operations required. The other edit distance formulas employ different methods, but they all measure the similarity between two strings as their outcome. This method is used to evaluate the similarity in operation names of different enterprise application software (EAS) systems. When an operation is performed in an EAS, a web service is requested to execute the original operation. Web service requests include meta-data (e.g., operation names, objects, field names, types, and values) [36]. When comparing two web services, their meta-data is evaluated using edit distance calculations to measure similarity. The motivation for this approach was to discover interoperability measurements that can be calculated and not impacted by human input such as surveys [36]. This approach offers an objective method for evaluating interoperability, relying on measurements rather than subjective opinions.

To perform the analysis, meta-data is extracted from the API interfaces of the EAS. An example of an interface in Swagger [37] is in Appendix B: Listing 1.

The schema of this interface is an example of an API interface used in an AES. The method by Valatavičius and Gudas employs edit distance calculation methods like Levenshtein, Jaccard, Jaro-Winkler, and Longest Common Subsequence to measure the similarity between web service API interfaces. The research suggests that drilling down to characteristics of EAS web-services can be helpful for determining similar objects which could be integrated [36]. It must be noted that this only considers analysis of a single request of each web service. The method looks for similarity between individual requests to find possible interoperability integrations. This does not include the analysis of the data structures of which the requests are part of to evaluate the schema of the web service.

This method evaluates the API interfaces of web-services to measure interoperability in the semantic interoperability layer. The goal is to identify similarities that could lead to integration and interoperability.

3.6 Organisational Interoperability Characterisation and evaluation using enterprise modelling and graph theory

Blanc-Serrier et al. [38]'s approach involves interoperability assessment based on graphical models. The method involves checking a set of rules on the graphical models to evaluate the degree of interoperability of the business processes. This approach primarily focuses on the organizational layer of interoperability.

There are various approaches to checking interoperability of two systems. The method by Blanc-Serrier et al, checks a set of properties inside the forged graph model of collaboration. The general steps for making and measuring a graph model of collaboration is as follows:

(1) Enterprise models of the organizations are made
(2) New model of collaboration between enterprise models is made
(3) The collaboration model of the two enterprise models is represented in a graph, according to Graph Theory [39]
(4) Mathematical rules are applied on the graph to highlight interoperability problems
(5) Rules detect exchanges that are poorly interoperable
(6) Improvement effort to operate properly is evaluated

Enterprise models can be created using a wide range of enterprise modeling languages, each with their own set of rules. However, the resulting collaboration model can be represented as a graph using Graph Theory [39]. The graph representation is a universal tool, making it possible to apply generic interoperability rules to the graphs and thus facilitating support for a wide range of enterprise modeling languages.

The collaboration graph is a simplified view of processes that highlights interoperability nodes and/or areas [38]. The nodes and/or areas in the graph representation enable mathematical rules to verify the interoperability of the systems.

Within the graphs, an organizational unit (person, group, department, etc.) is represented by a node. Each exchange between organizational units is represented as an arrow.

The rules that are described by Serrier et al. to mathematically check the graphs are stated below. An overview of the measurement is also provided.

(1) **Connectivity** - To achieve interoperability, a node must be connected to another node. Kosaraja's algorithm [40] uses depth first search to find connected nodes.
(2) **Feedback Loops** - Each node has to send feedback to each node from which it receives something, indicating a feedback loop for every piece of information sent. A matrix is created from the graph like Figure 2. The sum of a row is the score for a node.
    - score = 0, good feedback loop
    - score > 0, destination nodes do not refer back to the node
    - score < 0, does not send information back to other nodes
(3) **Critical Nodes** - Nodes which, if removed, split the graph into several parts. Details of the measure will not be discussed, algorithm defined in paper by Serrier et al. [38]. The algorithm

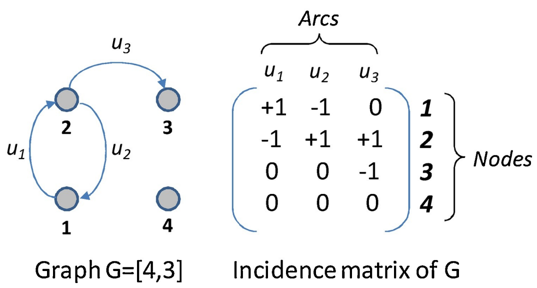

Fig. 2. Feedback loop measurement matrix [38]

goes from node to node by following the links. Non-connected nodes will not be studied, these cannot be critical nodes.

(4) **Longest Path** - Lead-time of each link added. Then calculates the route of the nodes with the longest duration.

(5) **Risk of non-interoperability** - Identifies parts of the collaboration graph where non-interoperability is of high risk
   a) **Highest number of arcs** - Define the path that has nodes with the highest cumulative amount of arcs.
   b) **Connections** - Path with nodes that compose the largest number of connections with other nodes.
   c) **Exchanges** - Path including the highest number of exchanges in a given period of time.

4 FINDINGS

Literature review on methods and metrics for measuring interoperability has identified that there are two major approaches to measure interoperability: the use of subjective maturity models and objective measurements.

4.1 Maturity Models

A maturity model is a framework used to assess and describe the various levels of maturity for a specific process within an organization. In the context of interoperability, a maturity model provides a framework for ranking the different levels of maturity in achieving interoperability. It may include assessment benchmarks to identify the current state of interoperability and provide a roadmap for progressing to a higher level of maturity in interoperability. Maturity models are a viable approach for assessing the level of maturity of interoperability. The key quality of these models is their ability to measure progress towards a goal. Maturity models are designed to be simple and survey-like, providing a scale and instructions on how to answer questions. The models typically base their questions on a set of criteria, as defined in the Interoperability Maturity Model by Knight [29], which requires respondents to choose from predefined levels. A cumulative score of the responses provides an assessment of the maturity level of the interoperability implementation.

Maturity models can also provide suggestions on how to improve interoperability by proposing ways to repeat the analysis at a later stage to compare scores. Additionally, groups of criteria can be analyzed together to generate scores that are divided into categories [41]. This approach can help to identify categories that are performing less well, thereby highlighting areas for improvement.

Many different maturity models exist. Some are tailored towards a sector, such as E-government [12–14]. Others are meant to be used for general interoperability assessment [29].

The literature review has revealed that maturity models for interoperability are influenced by the work of the Department of Defense of the United States of America, which presents the LISI Interoperability Model [31]. The LISI interoperability maturity model was developed for the US Navy to facilitate interoperability between processes for operational fulfillment. This model is a framework for achieving interoperability between various systems and components within the C4ISR domain, which stands for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance [42].

Maturity models for interoperability often draw inspiration from the LISI interoperability model [31]. This model is survey-based and uses questionnaires and a level-scale to answer the questions. Newer maturity models typically use similar scales for the levels but may improve or add questions.

4.2 Measurements

Performing measurements on business process models and API interfaces is an approach that uses mathematics and linguistic analysis to provide statistics about the state of interoperability. Like maturity models, these measurements cover both the semantic [43] and the organizational layer [36] of interoperability.

In contrast to maturity models, measurements focus on objective automated processes that can be executed on business process models to measure organizational interoperability, or API-interfaces to match ontologies in order to measure semantic interoperability. Although measurements may still include manual operations, such as model preparation, advancements in the techniques can also be made to automate these processes. Once the information is in the correct format, the computations can be carried out automatically, enabling easy repetition and facilitating continuous integration testing to gauge the level of interoperability.

Measurements are always limited to a specific format. The level of limitation depends on the implementation of the measurement. Methods can be limited by demanding a particular API-interface export format to assess semantic interoperability [43]. Not all API's have an export function like this. Thus, an interface in the required format might have to be made by hand. Alternatively, another approach provides more flexibility in terms of tools used. Business process models can be converted to a lower-level format that is better suited for interoperability analysis, which enables a wide range of inputs from various business process modeling methods [36].

5 DISCUSSION

The main finding is that there is a lack of standardized automated measures that can objectively analyze business process models and data, like API interfaces, to evaluate the level of interoperability.

This implies that there may be methods available to achieve interoperability, but these methods lack standardization by regulatory institutions. This is an important finding, because it is crucial that organizations that want to achieve interoperability between their software systems, are able to continuously integrate objective measures.

Previous research primarily proposes new methods to assess interoperability, often building upon existing questionnaires of maturity models. Some research show novel ways to measure interoperability. For example, automated string matching for ontology's. Within the literature, there are also articles that display challenges and future directions within the field of measuring interoperability. These pieces of work tend to focus on domain specific problems and possible solutions. This research is innovative due to its broader view upon the measurement of interoperability. For interoperability to exist, a wide range of software systems need to be able to integrate with another. This research highlights challenges of interoperability measurement that need to be addressed from the top view.

This research that has been conducted includes limitations. Information about methods and metrics to measure the degree of interoperability has been gathered from existing models, research about the challenges, and publications about improvements on models. The research did not consider expert opinions, nor results formed by a survey of subjects currently working within the field of interoperability. This narrowed view can limit the results of this research. A promising future direction for this research is the comparison of different methods within organizations. A set of approaches can be distributed across organizations looking to improve their interoperability. The progress of the organizations and the type of method can be recorded to find promising candidates for a standardized and automated approach for measuring interoperability. After conducting a systematic literature review, additional synonyms for the key terms of the search query were identified. For instance, "informational" can serve as a synonym for "semantic," while "process" and "pragmatic" can be used as synonyms for "organizational". Including relevant synonyms in the search query is crucial as it allows for a more comprehensive exploration of databases, especially those with advanced search capabilities. Neglecting to include these synonyms could potentially impede the quality and relevance of the search results obtained.

In short, this research provides a novel and insightful view on the current state of the methods and metrics for measuring interoperability. Nonetheless, the study is subject to due to time constraints and limited knowledge. Future directions for the research are provided to further analyze the field.

6 CONCLUSION

This study aimed to investigate the extent to which the current methods and metrics cover the field of interoperability. Through the analysis of literature it has been found that there are two types of approaches when it comes to evaluating interoperability. One of them is utilizing maturity models. Maturity models are methods to assess the current level of interoperability. Often existing of a set of five levels and a questionnaire. The levels range from not present (0) till fully integrated (5). These models are based on or propose improvements to the LISI [31] model.
An alternative method for measuring interoperability is the use of metrics and measurement methods. These methods are automated mathematical analyses of models [26], graphs [38] or ontologies [44]. The measurements within these methods are quantitative.

Current methods and metrics are diverse. There are various different opportunities for measuring interoperability. The problem that arises is that there is no standard for measuring interoperability. The lack of a standard for measuring, leaves organizations in an uncertain state about their specific assessment instrument. Current methods and metrics also come short in measuring interoperability by being centered around questionnaires. There is an insufficient amount of verified tools that help organizations with an automated way of measuring interoperability based on their existing infrastructure. The questionnaire's are susceptible to temporary perceptions and biases. Although a maturity model is an established method for assessing interoperability. The survey-based nature makes it less reliable, since the results can differ per iteration and the models do not provide ways for objectively measuring statistics. Automated testing can calculate the interoperability score based on the models and/or information about interfaces. This makes the method objective and repeatable for continuous integration testing. The major limitation of automated testing is its restriction to a specific format. The extent of this limitation depends on the method used. Certain methods offer greater flexibility in terms of the tools used, while others do not.

In conclusion, current methods and metrics cover the field of interoperability to a moderate extent. There is a large set of methods available to measure interoperability. Most of them being maturity models, since they are more universally implementable. Yet, there is a lack of standardized and supported methods to objectively measure the degree of interoperability through automated integration testing.

6.1 Future Work

A promising future direction for measuring interoperability is creating automated standards for measuring interoperability. The standardized measures should be specific to the layers of interoperability [2]. Existing automated measurements would have to be adapted or new ones have to be developed. The emphasis should be placed on objective measurements. These measurements should be applicable to a diverse array of systems, enabling fair assessments and minimizing bias. Standardizing and promoting such a method through institutions like the European Commission alongside the interoperability guidelines [2, 15], will improve the support and adaption of the methods to improve interoperability. Measuring interoperability this way through statistics about the interoperability configuration is a promising alternative. Automated methods can provide a more objective and consistent evaluation of models and interfaces, enabling organizations to assess the degree of interoperability more accurately. By using automated methods, organizations can identify potential issues and improve their interoperability, leading to better collaboration and more efficient business processes.

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A RESULTS ARTICLE SELECTION

Table 6. Selected Articles

Ref. No.	Organizational	Semantic	Context
[45]	X	X	E-gov
[41]	X		E-gov
[46]	X	X	IoT
[47]	X		
[48]	X		Enterprise
[49]	X		Sustainability
[50]		X	Automotive
[51]		X	IoE / Smart-Cities
[51]		X	IoE / Smart-Cities
-			
[51]		X	IoE / Smart-Cities
[14]	X		E-gov
[38]		X	Inter-organizational
[52]		X	Enterprise
-			
[53]	X	X	Inter-Organizational
[54]	X	X	Inter-Organizational
[55]	X		Inter-Organizational
-			
[56]		X	E-gov
[13]		X	E-gov
[57]	X	X	Inter-Organizational
-			
[26]	X		Business Processes
[58]			Supply-Chain
[12]			E-gov
[43]		X	Semantic Web

B SWAGGER API-INTERFACE

Listing 1. API-interface

```yaml
paths:
  /pets:
    get:
      summary: List of all pets
      operationId: listPets
      tags:
        - pets
      parameters:
        - name: limit
          in: query
          description: How many items to return at one time (max 100)
          required: false
          schema:
            type: integer
            format: int32
      responses:
        '200':
          description: A paged array of pets
          headers:
            x-next:
              description: A link to the next page of responses
              schema:
                type: string
    post:
      summary: Upload new pet
      ...
  /stores:
    get:
    ...
```