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Digital approaches to construction compliance checking: Validating the suitability of an ecosystem approach to compliance checking

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ABSTRACT

The lifecycle of the built environment is governed by complex regulations, requirements and standards. Ensuring compliance against these requirements is a complicated process, affecting the entire supply chain and often incurring significant costs, delay and uncertainty. Many of the processes, and elements within these processes, are formalised and supported by varying levels of digitisation and automation. This ranges from energy simulation, geometric checking, to building information modelling based checking.

However, there are currently no unifying standards or integrating technology to tie regulatory efforts together to enable the widespread adoption of automated compliance processes. This has left many current technical approaches, while advanced and robust, isolated. However, the increasing maturity of asset datasets/information models, means that integration of data/tools is now feasible. This paper will propose and validate a new approach of solving the problem of automated compliance checking through the use of an ecosystem of compliance checking services.

This work has identified a clear research gap. How automated compliance checking in the construction sector can move beyond sole reliance on BIM data, and tightly coupled integration with software tools, to provide an extensible enough system to integrate the current isolated software elements currently used within compliance checking processes.

To test this approach, an architecture for an ecosystem of compliance services will be specified. To validate this architecture, a prototype version will be developed and validated against requirements derived from the weaknesses of current approaches.

This validation has found that a distributed ecosystem can perform accurately and successfully, whilst providing advantages in terms of scalability and extensibility. This approach provides a route to the increased adoption of automated compliance checking, overcoming the issues of relying on one computer system/application to perform all aspects of this process.

1. Introduction

The lifecycle of the built environment is governed by a complex web of inter-related regulations, requirements and standards, ranging from contractual requirements, client requirements specified in the project brief and regulatory requirements. Ensuring compliance against these requirements is a complicated process, affecting the entire supply chain and often incurring significant costs [1]. Many of the processes, and elements within these processes, are formalised and supported by varying levels of digitisation and automation and thus provide great potential for integration into a wider digitised process. Examples of these existing tools include; energy simulation [2], geometric checking [3], to data lookup i.e. from Building Information Modelling (BIM) [4] and Geographic Information Systems (GIS) [5].

However, there are currently no unifying standards or integrating technology to tie regulatory efforts together to enable the widespread adoption of automated compliance processes [6]. Furthermore, current research in the area of automated compliance checking has traditionally focused on digitising sentences and simple clauses into a single machine executable output [7], generating automation at the level of an entire regulatory process which then requires the tight coupling of individual digitised elements of the process [4] or making the assumption that all requirements can be answered by data lookup i.e. BIM lookup [8] or GIS lookup [5].

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This has left many current technical approaches (i.e. geometric checking, lighting analysis, energy analysis etc…), while advanced and robust, isolated [1] and not yet related to building compliance checking. However, the increasing maturity of asset datasets/information models, means that integration is now technically feasible.

This paper will, thus, propose and validate a new approach of solving the problem of automated compliance checking through the use of an ecosystem of software services. This will answer the following research questions: (1) *Can the adoption of an ecosystem approach prove a viable option for the digitisation and automation of automated compliance checking* and (2) *What are the possible advantages of this approach; both the amount of compliance checks that are automatable, but also in terms of scalability and extensibility?*.

This paper will specify, implement and demonstrate the feasible adoption of an open ecosystem approach to digitised compliance, that will then be validated in the UK construction sector. This will demonstrate both integration of existing automated compliance checking capabilities into a coherent automated compliance checking ecosystem based on open APIs and the representation of digitised construction regulations in a standard format to drive the compliance checking process.

In the remainder of this paper; Section 2 will cover related work, Section 3 will outline the methodology, Section 4 will document the specification developed for an ecosystem based approach. Section 5 will describe the implementation of the ecosystem, with Section 6 then validating it. Finally, Section 7 will provide discussion and answer the research questions, with Section 8 concluding the paper.

2. Related work

This section will present a review of related literature, offering a summary of the current research landscape. Primarily, this focusses on automated compliance checking and digitised permitting, specifically looking at literature that has resulted in a demonstrable prototype or provides specific examples. Thus, work that focuses purely on theoretical contributions, such as the manual conversion of regulatory text into rules, is excluded.

A significant proportion of existing academic literature focuses on compliance checking, utilising only data that is already present in a BIM. The first significant piece of work in this scope was Singapore ePlanCheck, a tool for automated code checking in Singapore [9]. The Singapore ePlanCheck focused purely on checking data already present within a BIM model, using the Industry Foundation Classes (IFC) models as a bridge between its internal model and third-party BIM tools. Jeong and Lee studied BIM-based automated code checking for fire resistance and egress [10]. They created their algorithm following an iterative method that combines classification of building codes, extraction of requirements, extraction of BIM data and evaluation of missing information.

Zhong et al. proposed a metamodel of construction quality inspection and evaluation concepts [11]. The metamodel is implemented as a Web Ontology Language (OWL) ontology, which allows regulations to be expressed as a combination of OWL axioms and Semantic Web Rule Language (SWRL) rules. These authors used the Code for Acceptance of Construction Quality of Building Foundation as a case study. Sulankivi et al. used BIM-based automated compliance checking to avoid accidental inclusion of safety issues in the construction schedule [12].

Choi et also developed an evacuation regulation checking system, specifically validated against the Korean Building Code for high-rise and complex buildings [13], while custom checking rules are developed for this approach, they are tightly coupled to the underlying BIM model data. Following a similar approach, Hakim et al. proposed a classification system for automated compliance checking rules to support translation from plain language to computable language [14]. Sydora and Stroulia [15] presented a domain-specific language for computationally representing non-regulatory building interior design rules only and a method for evaluating rules in this language against a BIM model.

In 2015, RegBIM [4] was developed as an end-to-end methodology for regulatory compliance, underpinned by using IFC as a data model. The methodology behind the software includes; (a) the use of regulation experts to mark-up regulatory documents using RASE [16], (b) the use of BIM experts to map between the regulations and IFC data models, (c) the use of a rule engine (later a semantic model) to perform the compliance checking, and (d) a user interface to show the complex structure of compliance checking results to end users in an easily understood way. However, this work still had a strong link to IFC, requiring all data for compliance checking to be first present in an IFC model.

Other similar approaches have results in the development of domain specific languages, such as the Building Environment Rule and Analysis (BERA) language. This language was developed to define, analyse and check rules [17]. BERA is built on top of the Solibri Model Checker framework. While the use of the Solibri software provides this language with geometric calculation capabilities, it still exhibits a strong coupling to solely BIM model data.

Preidel and Borrmann introduced a semi-automated method for compliance checking using a visual programming approach. They demonstrate the method against an exemplary German fire code [7]. However, while this approach does not specifically link to the IFC schema, there is a strong coupling with building datasets.

Jiang et al. [18] proposed a grey-box checking technique and a BIM-based automated code compliance checking methodology that leverages ontology. The authors implement an automated code compliance checking platform against Chinese Building Codes. Also, Zheng et al. [19] use a mix of NLP and semantic alignment techniques to extract regulations from text documents and align the semantics found in the documents to those in an ontology that relates to IFC models. They then generate SPARQL queries based on this alignment. However, both of these approaches, while utilising semantic web technology, still rely on a direct transformation of BIM data into a semantic format.

There are, however, some examples of integration of compliance checking with other data sources. The LicA tool is a tool that automatically assesses the compliance of a building's water network design with a subset of the Portuguese domestic water systems regulations [20]. This work integrated hydraulic modelling and simulation into the compliance checking process, however this was done in a tightly coupled manner and would not be scalable to a wider scope of regulatory checks. Doukari et al. [21], demonstrate a bottom-up object centred approach for automated model checking and the corresponding plugin prototype. The authors present two case studies, one of which was a fire safety check against fire doors, the other which provides additional tightly coupled integration with BIM object library. Similarly, Zhang et al. developed algorithms for BIM-based automated safety checking [22]. The main contribution is a table-based safety rule translation algorithm. This approach leverages not only BIM data, but also integrates with scheduling data.

GIS data is also considered in the place of BIM data, to demonstrate this a study by Li et al. [23] applied NLP coupled with spatial reasoning to automate utility compliance checking. In this work, the NLP algorithm translates the textual descriptions of spatial configurations into computer-processable spatial rules. Spatial reasoning executes the extracted spatial rules following a logical order in a GIS to identify noncompliance.

Other works provide more possibilities for integration through their adoption of more standardised data models that can represent data beyond standard BIM data. Tan et al. proposed an approach to combine results from the thermal performance simulation of a building envelope with building codes to support compliance checking [24]. The approach relies on an extended BIM that also contains simulation results, thus extending the XML representations of the IFC schema and data (ifcXML) schema. Building codes are created manually in the form of decision tables derived from the targeted design regulations and their interdependencies. An off-the-shelf rule engine allows the user to define and execute the rules.

Nawari [8] defined a conceptual and theoretical framework to standardise the extraction of regulatory requirements from textual regulations for design review and proposed a modular architecture for the implementation of automated design review. This work proposed the Generalised Adaptive Framework (GAF). GAF is a process for computerising regulatory compliance checking based on an object-based representation of building regulations. It enables the translation of regulations into efficient, computable expressions. Using the GAF approach, Messaoudi [25] presented the development of a virtual permitting process for the state of Florida. Based on an analysis with local stakeholders, a virtual permitting framework is proposed using BIM. This work was subsequently further expanded and deployed in the post disaster recovery use case [26]. This approach still illustrates a direct link to BIM data, however, the adoption of XML does provide for future extensibility to other XML based data formats, however this has not yet been demonstrated.

Following a similar approach, Zhang [27] focused on the possibility of using current open standards for capturing requirements in the building industry to automatically check building models. Based on this, an approach was developed together with the ability to query related semantic and geometric information in building models. This work makes suggestions that it is possibly to query other data models such as GIS, but this is not demonstrated.

Utilising semantic technologies, Jiang et al. proposed a semi-automated green building evaluation framework based on an ontology that enriches BIM models with the required multidisciplinary data [28]. Their framework consists of a text knowledge extraction process, a BIM information extraction process, and an ontology building and reasoning process (combining semantic rules and a rule engine). However, there is still the requirement on all data being integrated into semantic model format prior to performing compliance checking.

Despite this significant amount of literature, only two papers have been identified that show wider levels of integration than discussed previously. Cheng and Das presented their web service-based framework for green building code checking and simulation [29]. Their approach, which utilises a rule engine and is based on Green Building XML (gbXML) models, evaluates and updates models iteratively by requesting input from multi-location cross organisational collaborators. Finally, Zhong et al. designed an ontology-based framework for building environmental monitoring and compliance checking [30]. The framework is built upon a BIM ontology (derived from ifcOWL), a sensor ontology (W3C's Semantic Sensor Network ontology) and an ontology of building regulations. SPARQL Protocol and RDF Query Language (SPARQL) queries are used to formalise the rules and constrains from building regulations.

To summarise these findings, Table 1 presents a summary of all work reviewed in this section that has produced a demonstrable demonstration of its capability. It summarises; (a) the type of the developed compliance checking tool, either web based (viewed in a web browser) or desktop based (a standard installed application), or accessed via API (application programming interface) (b) if the demonstration supported open data formats (i.e. IFC), and (c) categorisation into monolithic or service based architecture. In this sense, a monolithic system is defined as a system developed as a single unit, conversely, a services' architecture is software developed as a set of loosely coupled smaller services [31].

The literature review, summarised in Table 1, has provided an overview of existing work in the field of construction automated compliance checking. It is clear from this review that the vast majority of work in this field has focused on direct integration with BIM data, or integration with a single more standardised data format (i.e. XML or Semantic Web formats). Some work reviewed has integrated BIM data with external software tools, however in most cases this has led to a tight coupling between the implemented rules based system and that specific software. Few approaches have developed this in a more scalable way. The two identified papers that do tackle this both have limitations: Zhong [30] provides a semantic framework to achieve integration, but the practical aspects of integrating data from a variety of software tools is not considered. Cheng [29] outlines a web-services approach to solving this issue, but it is unclear if this can scale beyond the energy simulation example presented.

Table 1
Categorisation of related work.

Work	Type	Open data	Architecture
ePlanCheck [9]	Web	Y	Monolythic
Jeong and Lee [10]	Desktop	Y	Monolythic
Sulankivi et al. [12]	Desktop	Y	Monolythic
Choi [13]	Desktop	Y	Monolythic
RegBIM [4]	Web&API	Y	Monolythic
Preidel and Borrmann [7]	Application	N	Monolythic
Jiang et al. [18]	Application & API	Y	Monolythic
LicA [20]	Desktop	Y	Tightly coupled
Doukari et al. [21]	Desktop	Y	Monolythic
Zhang et al. [22,27]	Unclear	Unclear	Monolythic
Tan et al. [24]	Desktop	Y	Monolythic
GAF [8]	Desktop	Y	Monolythic
Jiang et al. [28]	Desktop	Y	Monolythic
Cheng and Das [29]	Desktop & API	Y	Tightly coupled
Zhong et al. [30]	API	Y	Services

This identifies a clear research gap; that there is a need to examine, in more detail, how automated compliance checking in the construction sector can move beyond sole reliance on BIM data, or tightly coupled integration with software tools. This will enable extensible approaches integrating the current isolated software elements currently used within compliance checking processes.

3. Methodology

This section will describe the methodology this paper will take to answer the research questions: (1) *Can the adoption of an ecosystem approach prove a viable option for the digitisation and automation of automated compliance checking* and (2) *What are the possible advantages of this approach; both the amount of compliance checks that are automatable, but also in terms of scalability and extensibility?*.

To test RQ1, an architecture for an ecosystem of compliance services will be specified. To validate this architecture, a prototype version will be developed and validated against the current manual checking process. To answer RQ2 the results of the validation and the view of industry members will be analysed to derive a set of advantages of the ecosystem approach to compliance checking

The context of this study will be energy, accessibility and fire safety in the UK non-domestic context. The motivation for these choices are:

- **UK Focus**: This paper will focus on the UK building regulations (specifically the UK Approved Documents). This scope has been primarily set because of the complex nature of the UK regulations and the experience of the authors with the technical content of these regulations. Furthermore, the UK regulations are of a representative level of complexity with many other countries. This provides a good illustration on how the ecosystem could be deployed in other countries.
- **Non-Domestic Focus:** This paper will focus on non-domestic buildings. The primary reason for this is that the increased complexity of non-domestic buildings and their regulations provides a richer basis for this study.

- **Energy, accessibility and fire safety**: These types of regulations will be selected because they are the three most significant regulations in the UK suitable for design time checking.

This paper will follow a three-step methodology:

Specification: In Section 4 the specification of an architecture for an ecosystem of compliance services will be developed, drawing from: (a) past work in the field, (b) an analysis of regulatory processes in the UK context and (c) an analysis of the regulations being considered.

Implementation: In Section 5, a prototype version of the ecosystem will be implemented, with necessary software components developed.

Validation: In Section 6, this will consist of two elements. Firstly, a demonstration will be conducted on a test building(a school) to validate that the ecosystem is able to successfully perform automated compliance checking, when compared against a manual assessment. Secondly, an industry facing consultation will be conducted in the pilot country to determine industry views on the ecosystem its validity and the feasibility of its deployment in the construction sector. Finally, the data collected from these elements will be collated and used to answer the research questions.

4. Ecosystem specification & architecture

This section will document the specification of the ecosystem and its architecture. The starting point for this, is previous work that elicited a roadmap for the adoption of automated compliance checking [1].

Previous work [1], discussed two levels of construction regulation digitisation. However, a third is now added to represent the complex needs of compliance checking processes in the built environment. These are defined below:

- **Machine-readable**: Where software can read, parse and understand the structure of regulation documents.
- **Machine-executable**: Where software can additionally execute actions based on the document.
- **Machine-operable**: Where software can instigate a set of complex processes based on the contents of a document.

This roadmap has generated an initial set of requirements:

- **R1**: Provide the automated checking of construction regulations, requirements, standards and guidance documents in a timely manner while maintaining human review and oversight.
- **R2**: Make these documents available in single human-readable and machine-operable form, enabling navigation, searching and querying.
- **R3**: Retain the ability for manual submission of information by human assessors.
- **R4**: Provide an audit trail of compliance checking, related to the regulatory clauses that generated the compliance checking so that decisions can be tracked.

From the review of literature conducted in Section 2, an additional two requirements have been elicited:

- **R5**: Enable the integration and formation of persistent links between a set of compliance checking services and data (including BIM models, calculation tools, data sources) that feature in current compliance processes.
- **R6**: Provide access to the ecosystem through the use of open APIs and standardised data formats.

The specification will be further developed with input from two key aspects; (a) the UK regulatory structure and (b) analysis of the regulations selected for this study. These will be discussed in the following subsections.

4.1. UK built environment regulatory structure

The regulatory structure for the UK built environment is highly devolved. The legislation is different for Scotland, for Northern Ireland, for Wales and for England. The controls on planning, including the regulation of building types and form, is mostly separate from the technical regulation of buildings. The technical regulation in England is led by the Building Act 1984[1] and the secondary legislation in the Building Regulations 2010.[2] Under the powers granted, the government maintains approved documents, each corresponding to the requirements in the secondary legislation.

The Approved Documents give methods for demonstrating compliance to the primary and secondary legislation, but there remains scope for offering alternative solutions which achieve the objectives or which achieve performance equal to those within the Approved Documents. Local authorities and, in some cases, third party assessors have powers to review building designs prior to work commencing, and powers to inspect the construction work. Two certificates must be obtained, the first that the design complies with the regulation, and the second that the completed building has been inspected and also complies. In practice, the inspection process can focus on ensuring that the construction matches the design in form and materials and that any matters unresolved during the design review stage are resolved on site.

The existing process of seeking Building Control approval is shown in Fig. 1. Assuming that no private certifier is commissioned, there are two actors shown in the two swim-lanes. The process is initiated by the Applicant (top lane, shown in salmon) when the design is ready by '(Re-)Sending the design to the Local Authority'. On receipt, the Local authority (lower lane, shown green) will 'Receive the Design and Assess Completeness' (and fees). If incomplete, the feedback loop 'Report incompleteness' (shown white) returns to trigger a re-send. If complete, the Local Authority will 'Inspect the Design and Consult fire (and sewer) authorities'. If rejected, the second feedback process loop 'Reject Design' also returns to trigger the applicant to re-send the design. If accepted, the Local Authority will 'Issue a Design Certificate' to the Applicant, which allows them to 'Start Construction'. The Local Authority will 'Initiate the Inspection Plan' and 'Perform Inspections' repeatedly until they are satisfied and then 'Issue a Construction Certificate' allowing the Applicant to 'Complete Construction and receive the Construction Certificate' prior to moving to 'Occupy'. The Applicant and Local Authority processes terminate separately.

It should be noted that the local authority is also obliged to keep on record a copy of design time approval documentation, as well as any inspection reports and documentation for their jurisdiction, this is independent of whether the inspection was performed by the local authority itself or a third party assessor.

The key requirement from this section that will feed into the ecosystem specification are:

- **R7**: Maintain a separation of responsibilities between producing construction regulations, assessing against those regulations and retaining the historical results of the compliance checking process.

4.2. Analysis of selected UK construction regulations

This section will document the analysis on the selected UK approved documents being considered by this study, to determine the types of components that will be required by the ecosystem in order to conduct automated compliance checking against these regulations. The three documents being considered are:

1 https://www.legislation.gov.uk/ukpga/1984/55.
2 https://www.legislation.gov.uk/uksi/2010/2214/contents.

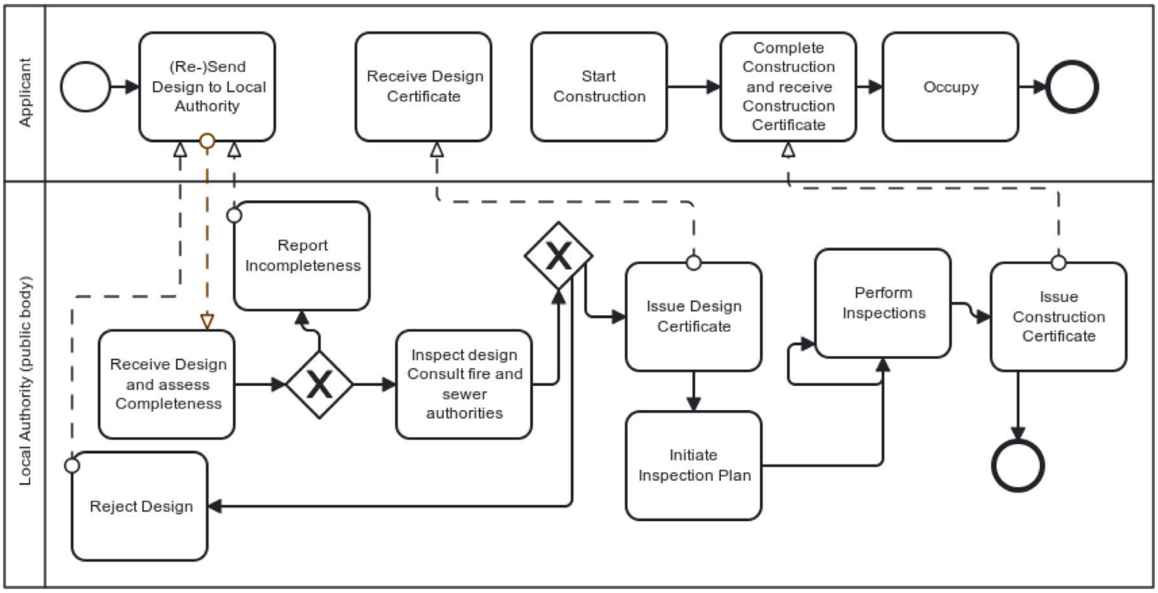

Fig. 1. Building control approval process.

- Approved Document L2A[3]: Conservation of fuel and power.
- Approved Document M2[4]: Access to and use of buildings
- Building Bulletin 100 (BB100)[5]: Design for Fire Safety in Schools.

It should be noted that BB100 is being considered because Approved Document B2, which documents fire safety regulations, does not consider school building types and instead requires designers to utilise BB100.

The goal of this analysis is to categorise the types of regulation clauses present within the documents into categories. The results are shown in Table 2 and a description of each of the categories is given below. It is worth noting that the BIM data category is for simple tests against values present in the BIM, where all the other categories provide additional specialist calculation on top of BIM data.

- BIM Data Lookup - checks against data stored in a BIM model.
- Product Data - checks again product data-sheets or data-sets.
- Colour Contrast - calculation of colour contrast values.
- Cross-reference - cross-references to other documents.
- Geometric - compliance checks that require geometric calculation.
- Energy Simulations - compliance checks that require the results of energy simulations.
- Other - compliance checks that are; (a) not checkable automatically mainly because assessment criteria are not specified, or (b) are specifically related to on site checks only.

From this analysis, it can be seen that in order to successfully perform automated compliance checking on these selected documents (listed above), the following software components capabilities, in addition to those of the ecosystem are required:

- **R8**: Checking clauses that require checks against data stored in a BIM model.
- **R9**: Checking clauses that require checks again product data-sheets or data-sets.

Table 2
Regulation clause classification.

Category	L2A	M2	BB100	Total	%
BIM data	62	391	398	856	52
Product data	13	20	47	80	5
Colour contrast	0	26	3	29	2
Cross-references	1	12	13	26	2
Geometric	2	244	147	393	23
Energy simulation	30	0	0	30	2
Other	80	96	65	246	14
Total	193	794	673	1660	100

- **R10**: Checking clauses that require calculation of colour contrast values.
- **R11**: Checking clauses that consist of cross-references to other documents.
- **R12**: Checking clauses that require geometric calculation.
- **R13**: Checking clauses that require the use of energy simulation data.

These software capabilities will feed into the overall ecosystem architecture, specifying some of the key services that must be provided by the ecosystem.

4.3. Ecosystem architecture

Based on the findings from the previous sections, this section will present the architecture of the ecosystem. For brevity, underpinning functionality such as authentication/authorisation is not shown. The architecture is shown in Fig. 2. The unique feature of this approach is that it is driven by the regulatory document, which is understood by the rule engine in order to orchestrate the compliance checking process; looking up the data source for the data required, locating the data source, retrieving the data and then computing final results based on that data.

As can be seen, the ecosystem consists of a set of ten components: **Compliance Document Service**: A core service that will provide access to machine-operable construction regulatory documents. These machine-operable documents will identify each checkable regulatory clause, each individual check or decision, and the relations between them (described in more detail in Section 5.1).

[3] https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l.
[4] https://www.gov.uk/government/publications/access-to-and-use-of-buildings-approved-document-m.
[5] https://www.gov.uk/government/publications/building-bulletin-100-design-for-fire-safety-in-schools.

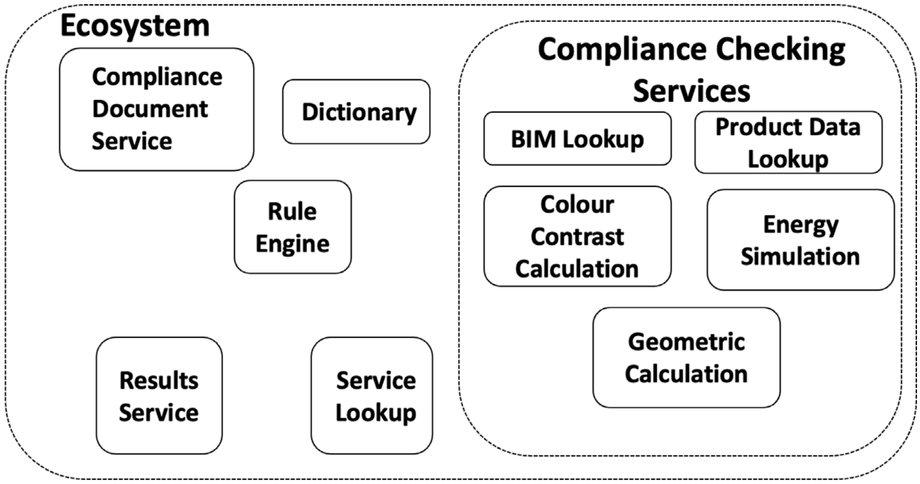

Fig. 2. Ecosystem architecture.

Result Service: A core service that will provide storage for results of compliance checks conducted and finalised.

Rule Engine: The core component and engine of the ecosystem. It provides the rule execution ability needed to conduct automated compliance check.

Data Dictionary: A supporting service that will provide concrete definitions of the concepts that appear in the regulation document to how that term can be located within a building model

Service Lookup: A support service that will provide a registry of all compliance checking services within the ecosystem

The remaining items in this list are the compliance checking services. These are the services that will perform the individual compliance checks within the overall compliance checking process.

BIM Lookup: A service that performs automated compliance checking based on BIM data lookup.

Product Data Lookup: A service that performs automated compliance checking based on product data lookup.

Energy Simulation: A service that performs automated compliance checking based on energy simulations

Geometric Calculation: A service that performs automated compliance checking based on geometric calculation.

Colour Contrast Calculation: A service that performs automated compliance checking based on colour contrast calculation.

It should be noted that the separation of the core components of the system into three core services (result service, rule engine and result service) is primarily taken to align with the separation of responsibilities described in R7; this means that the ecosystem can support the provision of the regulations, the compliance checking itself and the archiving of compliance checking results. In the UK these tasks are commonly performed by different organisations, so the ecosystem also supports this mode of operation by utilising standardised security approaches such as single sign-on and role based access control. These are implemented using standard protocols (OAUTH2) to promote extensibility and scalability.

Furthermore, the compliance checking services specified currently are those needed to meet the requirements of the Approved Documents being utilised in this study, conceptually this set of services can be further expanded as required. To achieve this, open APIs have been defined that use standard technologies (JSON/XML) to enable as lower barrier to integration as possible

To add extra detail, an example of how the ecosystem functions is illustrated in the UML Sequence diagram shown in Fig. 3. In this Figure the term "Compliance Checking Service" is used to refer to any of the compliance checking services in Fig. 2. This sequence diagram is a simplified example that represents performing a single compliance check on a regulatory document, aspects such as submission of manual assessments or addition of missing information are excluded for brevity. The data transfers noted in the sequence diagram are described below:

1. Submission of a API call documenting location of a model (as a model server URL) and a set of regulatory documents to check.
2. Retrieval of a regulatory document in JSON/XML form.
3. Retrieval of list and connection details of available compliance checking services.
4. Retrieval of definition of a given data item within a regulatory document i.e. which compliance checking service to utilise, data location in model etc.
5. Call to a compliance checking service to retrieve a given piece of data
6. Storing of results in compliance checking authority results server

This diagram shows the following important steps:

1. A member of the project team designing the building will submit a model to a rule engine for compliance checking. This will be done using a user-interface.
2. The rule engine will then retrieve the digitised form of the regulatory document that the model is to be checked for compliance against.
3. The rule engine will also retrieve a list of all compliance checking services that are available within the ecosystem.
4. The rule engine will then consider the regulatory clauses, the data-dictionary will be used to map regulatory clauses to a desired compliance checking service.
5. Once a compliance checking service has been identified, its endpoint will be looked up in the service lookup and a request for a given compliance check to be performed will be sent.
6. This process will be repeated until all compliance checks are completed.

5. A compliance ecosystem for the UK construction sector

This section will document the prototype implementation of the ecosystem of compliance checking services and provide more detail on how it functions. The implementation of each of the components described in Fig. 2 are described along with the APIs utilised. The developments presented in this section are available on GitHub.[6]

[6] https://github.com/D-COM-Network.

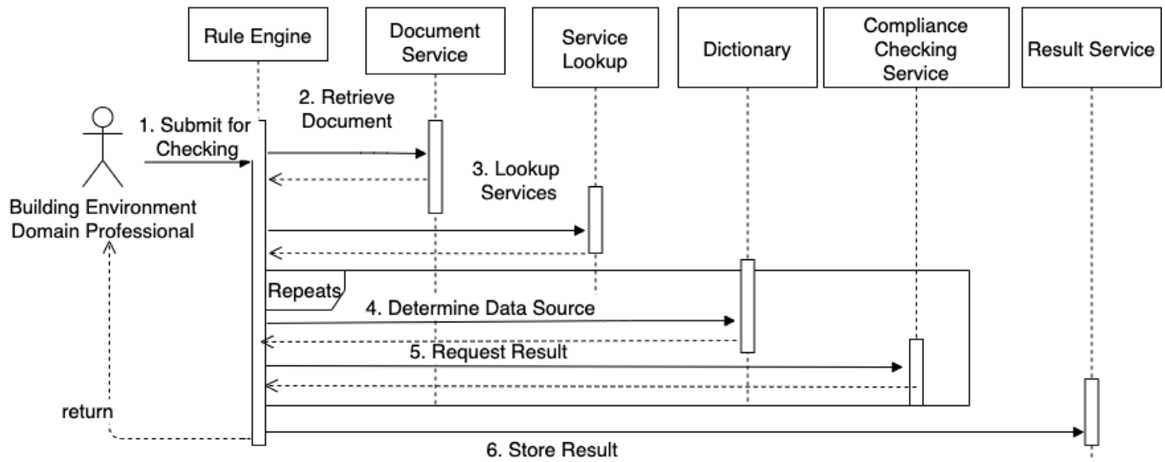

Fig. 3. Ecosystem sequence diagram.

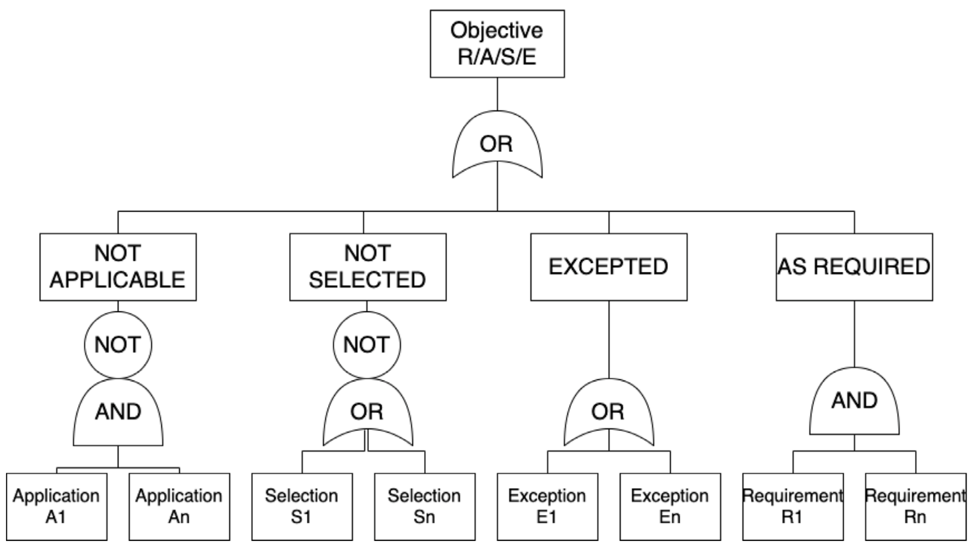

Fig. 4. RASE logical structure adopted from http://www.aec3.eu/.

5.1. Compliance document service

The compliance document service is a custom software component that provides access to construction regulation documents in a machine-operable way. The compliance document service exposes a single API that allows a user to request the content of a document, or a particular section/clause of a given document.

To deliver this, a JSON based representation was specified that formalises the structure of a regulatory document including concepts such as: (1) sections, (2) paragraphs, (3) figures, (4) tables and (5) cross-references.[7] The conversion of PDF documents to this JSON format was done through a PDF scraping process, following by manual validation and error correction.

This JSON structure is augmented with the use of RASE [4] to formalise each decision or check within the text and the logical relationships between these checks. RASE involves adding a set of tags to each section and item of text that generates a decision, how these are related logically is shown in Fig. 4:

- Requirement - which specifies the definitive requirements that must be met.
- Application - which restricts the scope to which the requirements apply.
- Selection - which further defines the scope to which the requirements apply.
- Exception - which allows the specification of exceptions to the rule being specified.

Furthermore, when adding a tag the following items of metadata may also be specified:

- A topic i.e. *type, width, height*.
- The comparison operator, i.e. =, >, <
- The target value.
- The Unit i.e m, cm, litres (optional).

This metadata provides a further level of formalisation of each decision. An example of a RASE tagged clause is shown in Fig. 5. In this example, we can see that this rule is for *Buttons*(Application), that are for *call* or *control* purposes (Selections). If a given button is in this scope then it must meet all the requirements. The figure identifies the Selections, Applications and Requirements using the tags ⟨S⟩, ⟨A⟩ and ⟨R⟩

[7] https://d-com-network.github.io/DCOMDocumentation/resources/compliancedocument.html.

<A>Buttons</A> for </S>call</S> and <S>control</S> <R>contrast visually with the surrounding face plate</R>, and the <R>face plate similarly contrasts with the surface on which it is mounted.</R>

Fig. 5. RASE example (Approved document M2).

5.2. Result service

The result service is a custom service developed to act as an immutable repository for compliance checking results. It provides a single API that is able to write (but not modify) results, additionally, several APIs are specified that allows the retrieval and querying of results. The result service stores the results of each compliance check, a cross-reference to relevant regulatory clause along with the identity of the compliance checking service that produced the result and any evidence produced.

5.3. Service lookup

The service lookup provides a directory service for the compliance checking services. It maintains a register of all compliance checking services and the endpoints at which they are exposed. This is important given there could be several alternatives for each compliance checking service. It also provides security, ensuring that only authorised compliance checking services can be registered. As this service lookup ability is a common problem in distributed systems, the Netflix Eureka service was utilised.[8]

5.4. Compliance checking services

A set of compliance checking services were also utilised in order to execute the regulatory documents chosen for this study. Compliance checking services are utilised by the rule engine component to provide responses to a specific decision i.e. *FloorArea > 100* m^2

To respond to these requests, each compliance checking service exposes a standard API that takes the following items as input:

- Data Item - The name of the data item *i.e. FloorArea*.
- Comparison - The comparison operator that should be used to test the data item against the target value. *i.e.* >.
- Target - The target value that should be tested against. *i.e. 100*.
- Unit - The unit of the target value. *i.e.* m.
- Global ID - A list of global IDs within the model upon which this compliance check should be performed.

A single API call either returns true (passed), false (failed) or unknown if the check cannot be performed. Evidence can also be returned in the form of file attachments, images or textual reports. The specific implementations of the services in this work are described below:

BIM Lookup: This compliance checking service provide the ability to answer simply BIM lookup queries. The *group* and *data item* data are used to locate a piece of information related to a given object (or set of objects) based on the *Global ID* provided. For each object, the located data item is then compared using the *operator*, *target* and *unit* parameters.

Energy Simulation: This service provides the ability to run an SBEM energy simulation[9] based on the free iSBEM software. When a compliance check is requested, a custom software component is run to convert the IFC model into the input format required by SBEM. Then the SBEM software is executed, and the output variables referred to by the *data item* are extracted and compared against the *target*, using the given *comparison* operator, with the defined *unit*. The group and Global ID parameters are not used by this service. Checking is assumed to always be done at the whole building level.

Geometric Calculation: This service is based upon the Solibri Office software package.[10] This service performs complex geometric calculations on BIM data. It works by providing performing calculations compliance checking on a given BIM object. A rule within Solibri Office is then triggered based on the *data item* parameter and the result is assessed against the *target* using the *comparison* and *unit* parameters. For this work, several custom geometric rules were implemented in Solbri Office. One of these is lobby dimensions checking.

Colour Contrast Calculation: The final compliance checking service performs colour contrast calculations. Given two objects in a BIM, it calculates the level of colour contrast present between them. The service utilised a standard formula to calculate colour contrast and (because no explicit requirement is provided in the regulations) a target value of 3:1 was utilised. This service receives *Global ID(s)* of spaces and utilises the *data item* to determine which items in the spaces to check the contrast of. This is then compared against the target ratio by checking against the *target* using the *comparison operator*.

Table 3
Data dictionary examples.

Term	Preferred service	Group	Data item
Floor area	Geometric	DCOM_Building	FloorArea
Air permeability At 50 Pa	Energy simulation	DCOM_Building	AirPermeability
Length is in accordance with Diagram 10	Geometric	DCOM_EntranceLobby	LengthDiagram10

5.5. Data dictionary

The data dictionary component provides a service that will provide concrete definitions of the concepts that appear in the regulation document to how that concept can be computed and/or located within a building model. Examples of this are shown in Table 3.

Table 3 shows three mappings, their preferred compliance checking service and the location in the IFC file that the data should be stored. While in many simple cases this could be achieved with a simpler lookup capability, in many cases terms may have differing meanings in different regulatory contexts, or there may be multiple different ways in which a given piece of data could be stored within a building model. Thus, a full data dictionary service is required to deal with these use cases.

Within the ecosystem the data dictionary was implemented using BRE Templater, which is an online service that provides data definition and mapping services[11]

[8] https://github.com/Netflix/eureka.
[9] https://www.uk-ncm.org.uk/.
[10] https://www.solibri.com/solibri-office.
[11] https://beta.bretemplater.com/.

```
RULE "M2_3_4"
WHEN
(
object.get("type") != "Button"
||
(object.get("purpose") != Call && object.get("purpose") !=
"Control")
||
(object.get("contrasts with faceplate") && ob-
ject.get("contrasts with surface"))
)
THEN
object.pass("M2_3_4")
END
```

Fig. 6. Simplified DRL.

5.6. Rule engine

The final component of the ecosystem is the rule engine. This is the component of the ecosystem that executes the compliance checking rules. It is built on top of the DROOLS[12] rule engine. A custom component translates the JSON regulation documents with RASE tags into executable DROOLS Rule Language(DRL) rules, and then executes them. This is done by utilising the logical formula shown in Fig. 4 to map each clause into two DRL rules (one to test if it passes, one to test if it fails). A simplified example is shown in Fig. 6 (based on the text in Fig. 5).

Each compliance check operates on the assumption that initially each rule should be applied to all objects in the building, with the applicability and selection statements filtering objects that do not need to comply with the regulations within that rule.

Within each rule, for each individual decision that rule engine utilises the data from the data-dictionary component to identify the required compliance checking service, and then uses the service-lookup to locate an endpoint for that service.

This process of identifying the compliance checking service to utilise is as follows: (a) the preference expressed in the data dictionary is tried first, (b) if that is not able to provide a result then a BIM data lookup service is tried, and (c) if neither of the previous steps have produced a result the result is flagged as needing human input.

Once the correct compliance checking service has been identified, the rule engine will make an API call passing the information described in Section 5.4 including the GlobalID of the object being considered. The compliance checking service will either return true, false or unknown. If an unknown is return the rule engine will either try another compliance checking service, or flag the rule for needing a human decision. This loose coupling means that any developer is free to develop their own compliance checking service which can then easily be used the central rule engine.

Due to this component utilising the robust DROOLs rule engine, it is able to optimise its execution of the regulations, so individual compliance checks are only executed when they are applicable and not excepted, i.e. if a particular compliance check is only required if the building is a hospital, it is not executed unless the building is a hospital. This is implemented by taking advantages of the lazy execution capabilities of this engine, meaning rules are only executed when needed, and within each rule as soon as enough information is known to determine an answer the remaining elements of the rule need not be tested.

[12] https://www.drools.org/.

Table 4
Requirement comparison.

Document	Clauses	Rules	Time
Approved documents L2A	37	115	83 h
Approved document M2	34	468	164 h
BB100	119	442	143 h

6. Validation

This section will describe the validation of the ecosystem of compliance checking services. Firstly, the compliance ecosystem will be demonstrated on a test building to determine if it is able to correctly perform compliance checking and ascertain if it meets the requirements described previously, this will be done using a comparison against the results of a manual compliance check. Secondly, a consultation will be conducted to determine the validity and the feasibility of deployment of the ecosystem in the construction sector.

6.1. Demonstration

The demonstration was performed on the three regulatory documents described previously. These documents were digitised in their entirety. Table 4 shows a summary, in this table, a clause represents an individual clause that includes regulatory content (i.e., excluding informational content and definitions) within the document, whereas a rule represents an individual decision point that was identified and formalised using RASE. This shows that L2A is clearly the shorter document, with a similar number of clauses but fewer rules. BB100 has more clauses — but fewer rules than M2, indicating that it has more, less detailed clauses. M2 has fewer clauses than either of the other two documents, but the most rules, indicating that M2 has a smaller number of more complex clauses. The time taken to digitise these documents is also shown.

The target building for the demonstration was part of a secondary school campus. It is designed for approximately 900 pupils, containing teaching spaces, dining areas and indoor sports facilities. It is also

Table 5
Requirement analysis.

R1	This is supported through the demonstrated results of both the coordinating ecosystem and the compliance checking services within it wherein it can successfully perform compliance checking, retaining manual oversight
R2	This is supported through the ability of the document service to expose regulation documents in a machine-operable form
R3	This is supported through the ability to allow human input through the user-interface. Supporting manual assessment of any elements that cannot be automatically assessed
R4, R5	These are both supported through the audit trial formed by the platform all results are stored in the result service, together with a clause reference and the compliance service that provided the result along with how the data was located (drawn from the dictionary service)
R6	This is supported though the open APIs supported by the platform[a]
R7	This is met through the separation of the document service, result service and rule engine. This represents the three key actors in the process; regulation owners, local authorities and the organisation performing compliance checking. Additionally role based access control is implemented within all components utilising OAUTH2 APIs
R8	This was met through the integration of the BIM data lookup compliance checking service
R9	This was not supported in the demonstrator as no product data sources were available, however, the APIs specified are able to meet these requirements once data sources are available
R10	This is supported through the integration of the colour contrast calculation service
R11	This is supported (assuming the cross-referenced document is digitised) through the rule engine's ability to refer to the results of compliance checks from other documents
R12	This is supported through the integration of rules executed within Solibri Office as a compliance checking service
R13	This is supported through the integration of SBEM within a compliance checking service

[a] https://d-com-network.github.io/DCOMDocumentation/.

designed to allow the wider community to use some of the facilities, such as the sports hall. The school is designed to be of modular construction and consists of a single two-storey building with the ground floor having a floor area of approximately 4600 m^2 and the first floor having a floor area of 2500 m^2. A federated IFC model was provided as follows: (a) architectural (177.8 MB), (b) furniture, fixtures, and equipment (81.3 MB), (c) structural (29.2 MB) and (d) mechanical and electrical (277.3 MB).

The automated compliance check was conducted, and the results visualised in a prototype user interface. The total time taken for the automated compliance check to execute was 102 min (it should be noted that 52 min of this time is the execution of SBEM).

Following an examination of the results, it was found that the outcomes of automated checking match those of a manual compliance check. This manual compliance check was undertaken by a qualified building control professional using PDF drawings (floor plans, elevations, and sections) generated from the model files. For comparison, the manual check took a total of 22 h.

This process also allowed a comparison against the requirements of the system shown in Table 5.

6.2. Consultation

The ecosystem of compliance services was also validated through a consultation exercise targeting the following groups:

- Facility and Asset Managers/Operators.
- BIM Professionals.
- Regulation Authors.
- Building Control Professionals.
- The Insurance and Liability sector.
- Health and Safety Professionals

Two consultation events were held, one face to face and one virtual. These consultation events firstly presented the ecosystem of compliance services and its validation and then asked for feedback, both generally, and specifically on the following specific points:

1. What is your feedback on the developed compliance ecosystem, its validation and its applicability for the industry?
2. What are the next steps required to realise the use of the ecosystem within the UK Construction Industry?

Overall, these events were highly successful, with 22 attendees (virtual) and 40 (in person). The feedback from participants is broken down below:

What is your feedback on the developed compliance ecosystem, its validation, and its applicability for the industry?

In general, attendees were positive regarding the developed ecosystem. Attendees felt this was a strong validation of the concept. Comments were made that the ecosystem was generally applicable (both to the UK industry and internationally). Specifically, attendees felt that the concept of the ecosystem could be applied beyond buildings, and discussions were also had around a refurbishment use case. A refurbishment use case may rely on a formal distinction between surviving, work, demolished work, and new work. This may require two models, or models with differing phases. This is layer of complexity that only the use of an ecosystem of components can support

Participants particularly liked the concept of the audit trail of results and that it forms a flow of information forming a historical record. Participants also agreed that varying stakeholders would need access varying levels of details of these compliance results for different reasons. Attendees viewed that this should be restricted due to security/privacy concerns, whilst others raised concerns around information overload.

Attendees were complimentary of the open API's, foreseeing increasing ease of deploying new functionality and additional compliance checking abilities. On this topic, attendees expressed that sustainability and adaptability would evolve over time, and so an ecosystem that can be flexible to accommodate this is beneficial.

Though generally positive, some concerns were expressed. Supply chain resource was specifically mentioned and barriers to BIM adoption in general were discussed at length, with concerns particularly around smaller organisations. Other attendees indicated concerns around losing knowledge of the building regulations within industry professionals. This topic was pervasive in discussions, with similar concerns being identified around the downgrading of roles due to an automatic system. Finally, a key concern is ensuring that the long understood requirements for paper based submission can be translated into guidance for what data must be submitted when moving to a model based submission

What are the next steps required to realise the use of the ecosystem within the UK Construction Industry?

In response to this, attendees expressed agreement in that the current standards are not designed to be machine-operable. It was the view of attendees that in the future, the machine-operable versions of documents (and human-readable versions that can be automatically produced from machine-operable versions), should be made available in the same way the PDF document are currently made available.

Attendees felt that to be successful in the next stage of development, baseline data and data standardisation would be key, particular requirements were the creation of BIM data requirements for automated compliance checking. An additional suggestion was the need for a methodology to assess and sustain consistency and accuracy across compliance checking services.

Another requested feature was the recording and formation of an audit trail of departures or concessions from the requirements in a given project. A suggestion was given to be able to visualise best practice and worst practice to find the “optimal view”, this could then be related to a percentage quality figure for a given project.

To answer research question 1 (*Can the adoption of an ecosystem approach prove a viable option for the digitisation and automation of automated compliance checking*) an architecture for an ecosystem of compliance services has been specified, implemented and validated. This process has demonstrated:

1. The integration of existing automated compliance checking capabilities into a coherent automated compliance checking ecosystem.
2. The representation of digitised construction regulations in a standard format to drive the compliance checking process.
3. APIs based communication to allow services within the ecosystem to interact.
4. The ability of the developed ecosystem to correctly perform compliance checking when compared to manual assessment.
5. The suitability of the approach for the UK Construction sector.

To answer research question 2 (*What are the possible advantages of this approach; both the amount of compliance checks that are automatable, but also in terms of scalability and extensibility?*) the results of the validation, along with industry feedback from our consultation event, has been analysed, and the following advantages elicited:

1. The advantage of an ecosystem based approach enabling the automation of an increased proportion of regulatory documents compared to approaches that adopt only a tight coupling to BIM data
2. The advantage of increased extensibility, allowing easier support of more compliance checking services as new regulations are digitised and existing regulations are updated.

Furthermore, some key recommendations for future activities in the field of automated compliance checking have been elicited from the results and consultation activities:

- The reworking of standards and regulatory documents into a logically driven form. Making machine-readable and human-readable versions of documents available in the same way the PDF document are currently.
- Creation of BIM data requirements for automated compliance checking.
- Development of methodologies to assess and sustain consistency and accuracy across compliance checking services.
- Representation and recording of audit trails of departures or concessions from the requirements in a given project.
- Utilisation of regulatory compliance data to visualise best practice and worst practice.

7. Discussion

The previous section has documented how the ecosystem of compliance services has been successfully demonstrated and validated. This has shown that across three key aspects that the developed ecosystem of compliance services offers tangible benefits;

1. **Correctness/Validity** - The validation on the school demonstration has confirmed that the ecosystem produces valid compliance checking results, when compared to a manual assessment.
2. **Suitability** - Attendees at the consultation events fed back that the ecosystem proposed was applicable to the UK industry and possibly internationally as well.
3. **Scalability** - From the analysis of the regulations performed previously (Section 4.2), it can be seen that the ecosystem, with the components developed, has the potential to automate 85% of a regulatory document. A system that is only able to perform BIM lookup based checks would only be able to automate 51% of a regulatory document. The remainder of the checks will require additional specialist computation of BIM data or data from other sources.
4. **Extensibility** - Participants at the consultations commented favourably on the extensibility of the ecosystem, specifically the development of open APIs was received favourably and the concept of attendees viewed that the ecosystem could be applied beyond buildings, and for refurbishment use cases.

To answer research question 1 (*Can the adoption of an ecosystem approach prove a viable option for the digitisation and automation of automated compliance checking*) an architecture for an ecosystem of compliance services has been specified, implemented and validated. This process has demonstrated:

1. The integration of existing automated compliance checking capabilities into a coherent automated compliance checking ecosystem.
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To answer research question 2 (*What are the possible advantages of this approach; both the amount of compliance checks that are automatable, but also in terms of scalability and extensibility?*) the results of the validation, along with industry feedback from our consultation event, has been analysed, and the following advantages elicited:

1. The advantage of an ecosystem based approach enabling the automation of an increased proportion of regulatory documents compared to approaches that adopt only a tight coupling to BIM data — elicited by analysis of the number of regulation clauses that could be checked by an ecosystem approach compared to a BIM only approach (Section 4.2).
2. The advantage of increased extensibility, allowing easier support of more compliance checking services as new regulations are digitised and existing regulations are updated - this was elicited through the experience of integration of multiple different compliance checking services as part of the validation, and comments from experts at the consultation event.

Furthermore, some key recommendations for future activities in the field of automated compliance checking have been elicited from the results and consultation activities:

- The reworking of standards and regulatory documents into a logically driven form. Making machine-readable and human-readable versions of documents available in the same way the PDF document are currently.
- Creation of BIM data requirements for automated compliance checking.
- Development of methodologies to assess and sustain consistency and accuracy across compliance checking services.
- Representation and recording of audit trails of departures or concessions from the requirements in a given project.
- Utilisation of regulatory compliance data to visualise best practice and worst practice.

8. Conclusion

This paper has proposed and validated a new approach to the problem of automated compliance checking through the use of an ecosystem of software services. This ecosystem aims to overcome current prevalent issues of implementing regulatory compliance checking capability into monolythic software tools. Thus, generating automation at the level of an entire regulatory process and building in an assumption that all requirements can be answered by BIM lookup.

The results of the development and analysis of the ecosystem approach has shown that the adoption of an ecosystem approach to automated compliance provides significant advantages. Supporting a higher level of automation, but also increased scalability and extensibility.

It is our view that the approach, presented in this paper, is necessary to allow the increased adoption of automated compliance checking. It is simply not possible to rely on one computer system/application to perform all aspects of this process. Instead, through the adoption of an ecosystem based approach, larger numbers of software vendors, academic developments and industry experts can contribute inline with their own expertise in a far more collaborative and ultimately scalable way.

CRediT authorship contribution statement

Thomas Beach: Conceptualization, Methodology, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Writing – original draft, Writing – review & editing. **Jonathan Yeung:** Data curation, Formal analysis, Investigation, Validation. **Nicholas Nisbet:** Methodology, Software. **Yacine Rezgui:** Conceptualization, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas Beach reports financial support was provided by UK Research and Innovation through the Industrial Strategy Challenge Fund

Data availability

Code is available at https://github.com/D-COM-Network Model data used is confidential and cannot be shared.

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References

[1] T.H. Beach, J.-L. Hippolyte, Y. Rezgui, Towards the adoption of automated regulatory compliance checking in the built environment, Autom. Constr. 118 (2020) 103285, http://dx.doi.org/10.1016/j.autcon.2020.103285.

[2] S. Seyedzadeh, F.P. Rahimian, S. Oliver, S. Rodriguez, I. Glesk, Machine learning modelling for predicting non-domestic buildings energy performance: A model to support deep energy retrofit decision-making, Appl. Energy 279 (2020) 115908.

[3] C. Preidel, A. Borrmann, Automated code compliance checking based on a visual language and building information modeling, in: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, Vol. 32, IAARC Publications, 2015, p. 1.

[4] T.H. Beach, Y. Rezgui, H. Li, T. Kasim, A rule-based semantic approach for automated regulatory compliance in the construction sector, Expert Syst. Appl. 42 (12) (2015) 5219–5231, http://dx.doi.org/10.1016/j.eswa.2015.02.029.

[5] Y. Demir Altıntaş, M.E. Ilal, Loose coupling of GIS and BIM data models for automated compliance checking against zoning codes, Autom. Constr. 128 (2021) 103743, http://dx.doi.org/10.1016/j.autcon.2021.103743, URL https://www.sciencedirect.com/science/article/pii/S0926580521001941.

[6] F. Noardo, D. Guler, J. Fauth, G. Malacarne, S. Mastrolembo Ventura, M. Azenha, P.-O. Olsson, L. Senger, Unveiling the actual progress of Digital Building Permit: Getting awareness through a critical state of the art review, Build. Environ. 213 (2022) 108854, http://dx.doi.org/10.1016/j.buildenv.2022.108854.

[7] C. Preidel, A. Borrmann, Towards code compliance checking on the basis of a visual programming language, J. Inf. Technol. Constr. (ITcon) 21 (25) (2016) 402–421.

[8] N.O. Nawari, A generalized adaptive framework (GAF) for automating code compliance checking, Buildings 9 (4) (2019) 86, http://dx.doi.org/10.3390/buildings9040086.

[9] T. Liebich, J. Wix, J. Forester, Z. Qi, Speeding-up the building plan approval–the Singapore e-plan checking project offers automatic plan checking based on IFC, in: E-Work and E-Business in Architecture, Engineering and Construction, Proc. of 4th European Conference on Product and Process Modelling, Portoroz, Balkema, Rotterdam, 2002, pp. 467–471.

[10] J. Jeong, G. Lee, Requirements for automated code checking for fire resistance and egress rule using BIM, in: International Construction Management Conference-Final Program & Abstract Book, Vol. 3, 2009.

[11] B.T. Zhong, L.Y. Ding, H.B. Luo, Y. Zhou, Y.Z. Hu, H.M. Hu, Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking, Autom. Constr. 28 (2012) 58–70, http://dx.doi.org/10.1016/j.autcon.2012.06.006.

[12] K. Sulankivi, S. Zhang, J. Teizer, C.M. Eastman, M. Kiviniemi, I. Romo, L. Granholm, Utilization of BIM-based automated safety checking in construction planning, in: Proceedings of the 19th International CIB World Building Congress, Brisbane Australia, 2013, pp. 5–9.

[13] J. Choi, J. Choi, I. Kim, Development of BIM-based evacuation regulation checking system for high-rise and complex buildings, Autom. Constr. 46 (2014) 38–49, http://dx.doi.org/10.1016/j.autcon.2013.12.005.

[14] S. Hakim, F. RE CECCONI, M.C. Dejaco, S. Maltese, et al., Rules complexity classification for automated compliance checking, in: Digital Proceedings of the 24th EG-ICE International Workshop on Intelligent Computing in Engineering 2017, eg-ice 2017, 2017, pp. 136–145.

[15] C. Sydora, E. Stroulia, Rule-based compliance checking and generative design for building interiors using BIM, Autom. Constr. 120 (2020) 103368, http://dx.doi.org/10.1016/j.autcon.2020.103368.

[16] N. Nisbet, J. Wix, D. Conover, The future of virtual construction and regulation checking, in: Virtual Futures for Design, Construction & Procurement, John Wiley & Sons, Ltd, 2008, pp. 241–250, http://dx.doi.org/10.1002/9781444302349.ch17, Ch. 17.

[17] J.K. Lee, Building environment rule and analysis (BERA) language and its application for evaluating building circulation and spatial program, 2011.

[18] L. Jiang, J. Shi, C. Wang, Multi-ontology fusion and rule development to facilitate automated code compliance checking using BIM and rule-based reasoning, Adv. Eng. Inform. 51 (2022) 101449, http://dx.doi.org/10.1016/j.aei.2021.101449.

[19] Z. Zheng, Y.-C. Zhou, X.-Z. Lu, J.-R. Lin, Knowledge-informed semantic alignment and rule interpretation for automated compliance checking, Autom. Constr. 142 (2022) 104524, http://dx.doi.org/10.1016/j.autcon.2022.104524.

[20] J.P. Martins, A. Monteiro, LicA: A BIM based automated code-checking application for water distribution systems, Autom. Constr. 29 (2013) 12–23, http://dx.doi.org/10.1016/j.autcon.2012.08.008.

[21] O. Doukari, D. Greenwood, K. Rogage, M. Kassem, Object-centred automated compliance checking: A novel, bottom-up approach, J. Inf. Technol. Constr. (ITcon) 27 (17) (2022) 335–362, http://dx.doi.org/10.36680/j.itcon.2022.017.

[22] S. Zhang, J. Teizer, J.-K. Lee, C.M. Eastman, M. Venugopal, Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules, Autom. Constr. 29 (2013) 183–195, http://dx.doi.org/10.1016/j.autcon.2012.05.006.

[23] S. Li, H. Cai, V.R. Kamat, Integrating natural language processing and spatial reasoning for utility compliance checking, J. Constr. Eng. Manag. 142 (12) (2016) 04016074, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0001199.

[24] X. Tan, A. Hammad, P. Fazio, Automated code compliance checking for building envelope design, J. Comput. Civ. Eng. 24 (2) (2010) 203–211, http://dx.doi.org/10.1061/(ASCE)0887-3801(2010)24:2(203).

[25] M. Messaoudi, N.O. Nawari, R. Srinivasan, Virtual building permitting framework for the state of florida: Data collection and analysis, 2019, pp. 328–335, http://dx.doi.org/10.1061/9780784482421.042.

[26] M. Messaoudi, N.O. Nawari, BIM-based Virtual Permitting Framework (VPF) for post-disaster recovery and rebuilding in the state of Florida, Int. J. Disaster Risk Reduct. 42 (2020) 101349, http://dx.doi.org/10.1016/j.ijdrr.2019.101349.

[27] C. Zhang, Requirement Checking in the Building Industry : Enabling Modularized and Extensible Requirement Checking Systems Based on Semantic Web Technologies (Ph.D. thesis 1 (Research TU/e / Graduation TU/e)), Technische Universiteit Eindhoven, Eindhoven, 2019.

[28] S. Jiang, N. Wang, J. Wu, Combining BIM and ontology to facilitate intelligent green building evaluation, J. Comput. Civ. Eng. 32 (5) (2018) 04018039, http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000786.

[29] J.C.P. Cheng, M. Das, A BIM-based web service framework for green building energy simulation and code checking, J. Inf. Technol. Constr. (ITcon) 19 (8) (2014) 150–168.

[30] B. Zhong, C. Gan, H. Luo, X. Xing, Ontology-based framework for building environmental monitoring and compliance checking under BIM environment, Build. Environ. 141 (2018) 127–142, http://dx.doi.org/10.1016/j.buildenv.2018.05.046.

[31] V. Lenarduzzi, F. Lomio, N. Saarimäki, D. Taibi, Does migrating a monolithic system to microservices decrease the technical debt? J. Syst. Softw. 169 (2020) 110710, http://dx.doi.org/10.1016/j.jss.2020.110710.