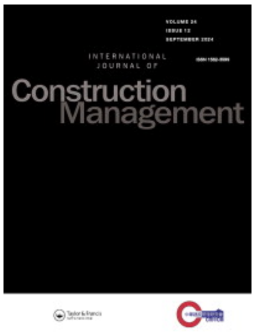

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Moving automated compliance checking to the operational phase of the building life-cycle: analysis and feasibility study in the UK

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ABSTRACT
Construction regulations ensure a base level of safety of built assets. Formal checking of built assets against regulations happens at defined points in their life-cycle, and often there is limited automation involved. The movement towards digitising and automation elements of physical site inspections paves the way towards a whole life-cycle approach for compliance checking. This paper explores whole life-cycle compliance checking. It does this by extending current checking processes which are common in the design and construction phases into the operational phase of the building life-cycle, proposing that the best way to achieve this is through automated/semi-automated data capture and analysis. To test the feasibility of this concept, this paper will review existing academic literature, analyse existing regulations and conduct proof of concept testing. This paper has found that the concept of whole-lifecycle compliance checking is becoming increasingly important to better monitor and assure high risks elements of the built environment. When applied to the operational phase, it, however, becomes impractical and expensive when relying on solely manual inspections. Furthermore, there is a significant quantity of viable use cases for this approach and that there are viable technologies to leverage them.

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Automated compliance checking; data capture; construction digitisation; building management

Introduction

Construction regulations are designed to ensure a base level of safety and performance of built assets (Nawari 2018). Currently, formal checking of built assets against these regulations happens at defined points in their life-cycle. These formal points of compliance checking include design time checking of building models (Beach et al. 2015), on-site inspections during and at the conclusion of construction, during refurbishment, and finally, retrospective checking in the case of an incident/accident.

Digitisation and automation of compliance checking is continuing to receive significant academic and industrial interest (Beach et al. 2020), and is anticipated to bring about significant impacts on industry productivity, including (Beach et al. 2020): (a) increased compliance certainty, (b) enhanced accuracy, transparency, and accountability and (c) accelerated reporting. This subject has been long studied, with multiple software tools developed for model based checking. These include DesignCheck (Ding et al. 2006) and the Singapore Building Control System (Goh 2008). To enable the extraction of construction regulations from documents, domain specific languages have been specified, including the BERA language (Lee et al. 2015). Conceptual and theoretical frameworks have also been defined to standardise the extraction of regulatory requirements from textual regulations for design review (Nawari 2019), enabling the translation of regulations into efficient, computable expression.

However, despite all of this work, there has not been significant adoption of automated compliance checking methods in the wider industry. Previous work has concentrated on model based checking against construction regulations (Beach et al. 2020), with little direct consideration of digitisation of the key inspection elements of a building's life-cycle. Importantly, the movement towards digitising and automated elements of physical site inspections also paves the way towards a whole life-cycle approach for compliance checking of built assets, which necessitates the extension of current checking processes beyond the design and construction phases, namely, the operational phase of the building life-cycle. Previous work (Beach et al. 2020) identified that 'Continuously checking the quality of assets using calibrated instrumentation and other data sources' was an important future requirement for the wider digitisation of compliance. This is becoming increasingly important as governments pay greater attention to the condition and maintenance of building stock. In the UK, in particular, the building safety bill (Ministry of Housing and Communities and Local Government 2020) requires owners of high risk assets to engage in regular assessments of building's and their safety risks.

Thus, this paper defines the concept of *whole life-cycle compliance checking of built assets* as; the process of continuously checking a built asset for compliance against a selected regulation, utilising instrumentation for data collection supported (semi)automatic decision-making tools.

This paper tests the feasibility of future research in this area by answering the following research question: *How can whole life-cycle compliance checking of built assets make use of data capture and automated checking technologies?*. The remainder of this section will outline the methodology and summarise the remaining sections of the paper.

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Methodology

This paper will employ the following specific steps to answer the above research question:

- **Literature Review:** A literature review will be conducted to identify existing examples and utilise technologies relevant to whole life-cycle compliance checking. To conduct this review, the following process will be followed:
    1. A broad search will be conducted using Scopus based on the following keywords *compliance AND (automated or automation)* within the engineering domain (N = 1,564).
    2. These paper are filtered based on title abstract to only include papers that include; checking against regulatory requirements in the operational stage and the use of an automated approach (N = 45.)
    3. Remaining papers were categorised into technologies used, and the most recent applications in each case were selected for presentation (N = 25).
- **Review of UK Approved Documents:** Reviews the non-domestic regulations within the UK construction sector to determine which areas of the UK regulations the concept of whole life-cycle compliance checking is applicable to and to identify initial demonstrators based on the relevant technologies identified previously and use cases of these technologies within the regulations for further study.
- **Demonstration:** Based on the previous item, demonstrate and analyse the technical feasibility of the concept through proof of concept demonstration.
- **Feedback and Review:** Review the prototype technical feasibility results with industry via an industry feedback session.
- **Validation** Validate the results by analysing industry attitudes towards automated compliance checking and gathering their assessment of the feasibility of the prototypes.

This paper applies the following limitations to its scope:

- **UK Focus**: This paper will focus on the UK construction regulations (specifically the UK Approved Documents). This scope has been primarily set because of the increased interest in the UK currently in monitoring the compliance of building stocks, this is shown by the introduction of the Building Safety Bill (Ministry of Housing and Communities and Local Government 2020).
- **Non-Domestic Focus:** This paper will also focus on non-domestic buildings. The primary reason for this is that the increased complexity of non-domestic buildings provides a richer basis for this study. Furthermore, commercial building owners, due to the legal responsibilities placed on them, are the most likely audience for whole-lifecycle compliance checking when compared to individual domestic property owners.

In the remainder of this paper, Section 3 documents the literature review of whole life-cycle compliance checking and relevant technologies. Section 4 presents the review of the UK regulations, and the selection of target regulations for this paper. Section 5 discusses the proof of concept demonstrators created. Finally, Section 6 presents findings and industry feedback, and Section 7 concludes the paper.

Literature review

Building inspections are required to be carried out at various points during the construction process, and, once completed, the building is not subject to further building control measures, unless retrofitting work that requires new building control approval is conducted. However, despite this lack of formal re-inspection, there are still significant requirements placed upon commercial building owners regarding the health and safety of those in their buildings. This has given rise to a variety of existing approaches that are taken to automate various building inspection and monitoring processes these are essential to establish whether a building is compliant with safety and performance based regulations, thus aiming to identify deficiencies in the safety or performance of the building.

One of the most common forms of building performance monitoring is for building energy consumption (Ahmad et al. 2016). Energy monitoring technology has advanced significantly and there are now sophisticated tools to monitor and interrogate energy usage data (Lee et al. 2016), however these mostly focus on energy or financial savings rather than compliance checking of energy usage against environmental regulations. Other common processes involves monitoring fire safety. This includes the maintenance of functional and fit-for-purpose equipment in a building, as well as verifying occupant compliance with fire safety rules. Initially, many of these processes relied on non-digital methods. However, more recently, audit processes have benefited from digitalised methods of documentation and communication. The collection and evaluation of evidence has become faster and more efficient through digital processes (Nearon 2005).

Technologies are now also being increasingly utilised to support, but not automate, these processes (Wang et al. 2015; Chen et al. 2020). However, these advances provide support to human decision makers performing manual processes and do not attempt to automate the processes in any way.

The remainder of this section will focus on reviewing the current state of the art (from both industry and academia), focusing on automation of building monitoring and compliance checking processes.

Based on this process the results of this review has been categorised into five broad technology areas; (a) Thermography, (b) Image Recognition & Object Detection, (c) Laser Scanning/ LIDAR Measurement, (d) Internet of Things based Building Monitoring and (e) Photometry. Each of these areas will be reviewed in one of the following subsections.

However, firstly, the section will contextualise the concept of who-lifecycle compliance checking within the context of existing state of the art in the field of automated compliance checking.

Integration of operational phase lifecycle compliance checkingwith existing compliance checking research

Currently, within the field of automation of construction compliance checking generally, three broad approaches have been taken; (1) pairing of constructions regulations and executable code, (2) fusion human-readable and machine-readable elements and (3) use of automated Natural Language Processing (NLP) to automate checking based on human-readable documents.

The pairing of construction regulations and executable code primarily consists of manual and semi-automated approaches to converting human-readable regulations into executable code in a variety of formats and languages. This includes the development of new languages such as Building Environment Rule and Analysis

(BERA)(Lee 2011) or using existing languages (Gherkin)(Moult and Krijnen 2022) or visual programming (Preidel and Borrmann 2016).

Other approaches commonly taken are the fusion of human-readable regulatory text and machine executable meta-data, allowing a single document to represent both human-readable and machine-executable regulations. The most common representation used in this area is RASE (Hjelseth and Nisbet 2011).

The final approach taken is the automated translation of regulatory documents into machine-executable code. Recent advancements in this field include using rule-based semantic natural language processing techniques to automate the extraction and the machine-process-able representation of regulatory requirements from textual regulatory documents (Zhang and El-Gohary 2015). The combination of Natural Language Processing (NLP) with with spatial reasoning has also been developed (Li and Cai 2015) has also been developed as a means for automatically extracting and formalising regulatory content. Finally, the use of NLP and semantic alignment techniques to extract regulations from text documents has been successful in aligning the semantics found in the documents to those in an ontology that relates to building data models (Zheng et al. 2022).

Regardless of the process involved there is a need to align the terminology between those used in the regulatory texts with data or technologies that can be used to conduct the actual compliance checks. These mappings may vary based on building lifecycle stage, wherin in the design stage checking may be based exclusively on BIM datasets, while in operational stage technologies such as those reviewed in the follow subsections may well be required. A common approach for achieving this, that has already seen success, is the use of dictionaries to formalize these mappings (Beach et al. 2024).

Thermography

A building's energy consumption and heating/cooling retention is one of the most significant metrics of building performance for asset owners, This is quantified as the thermal transmittance (U-value) (Aditya et al. 2017). Direct verification of the performance of a building's fabric during a building's operational life is rare, especially when detailed information of the materials used during construction are no longer available.

Many studies have been carried out which consider the use of quantitative infrared thermography (IRT) for determining U-values. This method is thought to be advantageous in its fast measurements, and practicality for multiple sites of inspection. However, its application and accuracy is uncertain, with many strengths and limitations having been identified. Compared to heat flow meter (HFM) measurements, IRT measurement has large surface temperature measurements (Danielski and Fröling 2015) and shorter test duration (Fokaides and Kalogirou 2011). However, IRT is greatly susceptible to deviations in U-value measurements as a result of increasing wind speed (Albatici and Tonelli 2010). As such, its application for outdoor vs indoor use has been debated (Grinzato et al. 1998).

Currently, in the literature, both inside and outside applications of IRT were tested. Inside measurements were advantageous due to the controllable boundary conditions, which improve accuracy (Albatici et al. 2013). Conversely, external measurements were susceptible to disruptions from environmental factors and thermal reflections (Tejedor et al. 2017). To overcome such limitations, testing is typically conducted in specific climates. Alshatshati et al. (2016). Such limitations were overcome for indoor measurements either by direct measure of indoor weather conditions or the use of a centralised building information management system (Ham and Golparvar-Fard 2015). Alshatshati et al. (2016) also implemented a genetic algorithm (GA) optimisation to minimise the error in calculated U-value with thermography versus actual value.

U-value measurements for windows prove more challenging than walls and doors. The opacity of glass to wavelengths of light at 3-14 um cause specular reflections (Baldinelli and Bianchi 2014). Consequently, radiation can compromise the accuracy of IRT testing of glass (Taylor et al. 2013). Specular reflections of surrounding objects, inaccurate estimations of ambient temperature and treatment of the glass can all contribute significantly to errors in IRT testing (Krenzinger and Andrade 2007; Maroy et al. 2017). Krenzinger et al. suggested the use of additional devices to establish a reference point to correct the reflection errors, as well as the use of equations considering multiple angles of incidence for the IRT.

Image recognition & object detection

Methods encompassed by AI, Computer Vision, and image recognition have been implemented to improve processes across construction. Image recognition involves techniques for detecting patterns in and analysing images that can be automated to carry out a process.

Within the field of construction and the built environment, several use cases for image recognition of and object detection have been explored. The primary use cases explored have focused around the use of object recognition as part of a pipeline for constructing as-built BIM models from LIDAR scan data (Wang et al. 2020). Other use cases include image recognition of construction site status (Wu et al. 2010) or vehicle tracking (Lu et al. 2007). The closest examples to regulatory compliance checking found in literature include the use of image recognition to detect damage (Xu et al. 2019) and detecting unsafe on site situations (Zhang et al. 2020)

However, based on the literature in this area, while there are examples related to compliance checking, there are no examples of the use of image recognition/object detection that closely link the technology to constructions regulations themselves.

LIDAR and other measurement technologies

The use of LIDAR to conduct measurements within buildings has been common (Forlani et al. 2006). One of the most common usages, currently, is the production and use of 3D point clouds to allow for a detailed capture of a structure (Tang et al. 2010). The most common use of point cloud data is for the implementation of the Scan to BIM concept (Werbrouck et al. 2020). Once reconstructed, such a BIM model can be used for compliance checking in much the same was as a BIM model created during the design process. However, Scan to BIM is a reasonably heavyweight process if compliance checking is the only goal.

Other measurement techniques include the use of measuring devices such as a total station or mobile phone (Ozcan 2014) to record individual points. However, the applications are usual associated with drawing floor plans, or taking measurements for manual analysis. To date, no exploration of these devices in the context of automated regulatory compliance checking has been undertaken.

The internet of things based building monitoring

IoT has excellent prospects for its use in built environment asset monitoring and regulatory compliance checking (Tang et al. 2019) Currently, IoT monitoring of built assets has been used in a variety of use cases.

For energy management, IoT devices are commonly either attached to individual building systems/components or existing meters, data is then collected and reported to facilities managers (Bottaccioli et al. 2017; Chang et al. n.d.). Another IoT use-case is the continual monitoring of health and safety of workers (Barata and da Cunha 2019), however these focus on monitoring workers against hard-coded warnings and alerts based on the sensor data rather than checking against relevant regulations.

IoT has also been utilised to monitor other building parameters that have a direct relevance on building compliance, this includes occupancy monitoring (Akkaya et al. 2015) monitoring radon gas levels in buildings (Blanco-Novoa et al. 2018).

Photometry

Another candidate technology that could be utilised to gather data for use in regulatory compliance checking is photometry. One of the more common relevant use-cases of this technology is for recovering surface shape.

An example of this (Higo et al. 2009) presents a simple 3D modelling method for recovering surface shape and reflectance from a set of images. Previous works typically have several limitations in practice, these are usually: the need for fixed or known camera and light positions, a dark room, an orthographic camera model, and a Lambertian reflectance model. It is often difficult to fit all these constraints in real world situations. The authors of this paper improve upon previous works by removing all these constraints. In these works, a point light source has been attached to a handheld camera, adding a photometric constraint to the multi-view stereo problem. With this constraint, the authors were able to simultaneously solve for shape, surface normal, and reflectance.

This was then built on (Gendy and Shalaby 2007; Alamdarlo and Hesami 2018), who utilised photometry to recover surface texture from pavements. However, this was not without issues, as the dark monotone of pavement surfaces requires high illumination intensity to produce a reasonable variation in surface reflectance (Gendy and Shalaby 2007). They proposed a four-source photometric stereo system. A digital camera and four light sources were mounted in a retractable frame to allow height and angle adjustments. This technique required a minimum of three images under three different directions of incident illuminations whilst the viewing direction was held constant (Gendy and Shalaby 2007). Alamdarlo further examined pavements with varying texture types, investigating the optimal angles for the four source system (Alamdarlo and Hesami 2018).

In summary, there have been very few use cases of Photometry that are relevant to the concept of whole-life-cycle compliance checking, and there has, so far, been no instances of its utilisation directly for regulatory compliance checking.

Summary

This section provided two key conclusions; (a) there have been specific developments and research case studies i.e. U-Value prediction, pavement surface recognition and the use of LIDAR in as-built BIM that show great potential in this area, (b) the vast majority of current work in this area are designed to automate data collection by a human assessor and not provide any automated or semi-automated capability for decision-making based on this data collection and (c) generally there are very few, if any, examples of these technologies being directly utilised for the purposes of regulatory compliance checking considering the accuracy, reliability, and practical considerations that go with this use case.

UK regulation analysis & regulation selection

This section documents the review of the UK Approved Documents. The goal is to determine which areas of the UK regulations the concept of whole life-cycle compliance checking is applicable to, and to identify initial priority areas for further study. In the UK, the building regulations are high level minimum standards for the design, construction, and alteration to virtually every building type. Building Regulations Approved Documents set out detailed practical guidance on how to achieve compliance with the regulations. There are a total of 18 approved documents, These are Approved Documents A, B, C, D, E, F, G, H, J, K, L, M, O, P, Q, R, S and 7 (UK Government 2022).

To ascertain the applicability of the UK regulation's to whole life-cycle compliance checking, these approved documents were reviewed according to the following methodology:

1. **Document Inclusion:** Each approved document's scope will be reviewed, and based on the scope a decision will be made if it will be analysed in detial.
2. **Clause Identification:** Each clause in the retained approved documents will be analysed, to determine if it is applicable to compliance checking in the operational phase of a building's life-cycle.
3. **Expert Review:** The selected clauses are reviewed by a building control professional and either retained or discarded.
4. **Technology Allocation:** The final list of retained clauses will be analysed and allocated against a technology type as defined by capabilities of the technologies reviewed in Section 3.
5. **Demonstrator Selection:** Demonstration to be developed will be selected from the most commonly selection technologies in order to demonstrate their feasibility.

Document inclusion

This paper's scope of on non-domestic regulations led to the exclusion of Approved Documents Part D, Part P, Part Q, Part R and Part S as they are not applicable to the non-domestic scope. Additionally, Part E has also been excluded due to the existing, well-developed methodologies for on-site sound insulation testing that are already widely adopted in the UK. All other approved documents were retained.

Clause identification & expert review

A total of 74 candidate clauses were identified following the initial review of the in scope documents and subsequent expert review

Technology allocation

In this phase a desk study as performed to compare each candidate regulation, with the capabilities of the technologies reviewed in Section 3. This allocation is summarised in Table 1. Each row of the Table illustrates one of the approved documents against which an in-use non-domestic building could be checked. The columns represent applicable the number of clauses within that document found applicable to a given technology.

Demonstrator selection

The two most common technologies, photometry, and LIDAR were selected to provide proof of concept prototypes. Demonstrators were not selected for the IoT use case due to the fact that the use of IoT is already becoming commonplace in the built environment, as evidence by literature presented in Section 3. Equally, due to the fact there is only a single regulation that can make use of thermography this was also not selected for a demonstrator. To select which specific clauses would be developed, the following process was undertaken:

From further analysis of the 74 candidate regulations, it was determined that:

- 5 clauses had available technology to check – but gaining access to actually take measurements would be difficult/impossible. Either because of height or because they are not accessible (behind walls, underground etc …).
- 10 clauses currently had no commercially available technology to enable measurement
- 1 clause had little value in taking an automated approach – due to the simplicity of the regulation
- 9 clauses could not be checked with technology however, a semi-automated approach of guided human assessment could be implemented.
- 2 clauses already had established automated checking methodologies in usage.

This left a total of 47 clauses that were, based on our analysis, feasible for further examination. The specific clauses that were selected were from Approved Document B (Fire Safety) and are described in the following section.

Proof of concept demonstrators

This section describes the proof of concept demonstrations that were constructed to validate the feasibility of the applicability of the whole life-cycle compliance.

The aim of the development of these proof of concept prototypes was to demonstrate the viability of conducting whole-lifecycle compliance checking of a given regulatory clause. Analysing and showcasing the potential of this avnue of work. Thus, these prototypes are not designed to be exhaustive but simply demonstrating the validity of this given technology for performing checking in the operational phase.

Photometry/Object Detection - A demonstrator in checking for the presence of valid fire door signage and the detection of fire door damage is tested. Current practice is that inspection of fire doors is done manually by an individual with expertise in this area to ensure it is done correctly. This use case will utilise image recognition to determine if these inspections can be automated.

LIDAR Measurements - A demonstrator for checking of fire escape route compliance is developed and tested. Currently, there is no routine assessment of a building against these regulations after it has been constructed. Introducing these checks could benefit both existing asset owners who wish period checks on compliance of their assets, and new asset owners wishing to understand their compliance risks. Manual checking of fire escape route compliance would require detailed measurements of many spaces throughout a building, measuring and recording these measurements accurately manually would be time-consuming and error-prone, additionally, the technical requirements of the regulations that must be checked against are complex and checking them requires significant expertise in this highly specific area. Thus, this use case will explore how the use of LIDAR scanning could automate these checks.

LIDAR measurement – checking of fire escape route compliance

This section describes the prototype developed for geometrical checking and fire escape route compliance. The work in this section has largely targeted the fire safety guidance provided in *Approved Document B: Fire Safety.*

The primary advantages of automated checking of these particular regulations are; (a) they require detailed measurements of many spaces throughout a building, measuring and recording these measurements accurately manually is time-consuming and error-prone, (b) the technical requirements of the regulations that must be checked against are complex and checking them requires significant expertise in this highly specific area. The use of an automated checking approach provided by this demonstrator allows the automating collection and management of the large quantity of measurement data, but also allows compliance checking to be conducted by any competent individual even if

Table 1. Summary of regulation analysis on chosen documents (T=thermography I = IoT L = LIDAR P = Photometry).

Part	Document	T	I	L	P
A	Structure	0	0	3	0
B	Fire Safety	0	4	8	2
C	Site Preparation and Resistance to Contaminants and Moisture	0	0	0	1
F	Ventilation	0	3	0	1
G	Sanitation, Hot Water Safety and Water Efficiency	0	0	0	1
H	Drainage and Waste Disposal	0	0	5	3
J	Combustion appliances and Fuel Storage systems	0	0	2	4
K	Protection from falling collision and impact	0	0	4	4
L	Conservation of fuel and power	1	1	0	1
M	Access to and use of buildings	0	1	8	8
O	Overheating	0	0	3	6
	Total	1	9	33	31

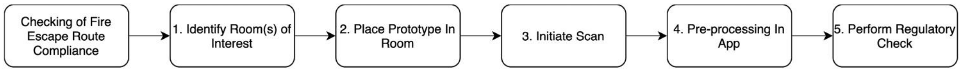

Figure 1. The prototype device process.

they do not possess the technical expertise in fire safety regulations.

The prototype that has been developed comprises 3 elements; (a) RPLIDAR S1 – a low cost USB 360 degree 2D laser scanner, weighing 105 g and with a range up to 40 M (b) a monopod and (c) a Raspberry Pi. The prototype and its user interface is shown in Figure 1.

To drive this prototype an application has been developed comprising a GUI, data post-processing and calculations related to pre-selected regulations from Approved Document B. The application is capable of checking 2 demonstrative regulations; Regulation 3.16 Simultaneous Evacuation and Regulation 2.10 Alternative Escape Routes. These regulations were chosen to demonstrate the range of geometrical checks that the prototype is capable of checking. A large majority of regulations in both Approved Document Part B are geometrically related to these two demonstrations.

Figure 1 illustrates the both the device and GUI which encapsulates a point cloud, captured and generated by the LIDAR device. The floorpan seen in the figure is generated from a point cloud, as captured by the LIDAR device. This is representative of raw data captured by the scanner device.

The process a user of the prototype follows is that they (1) identify room(s) of interest, (2) place the prototype with clear line of sight to all walls and other elements of interest, (3) initiate scan, (4) performing any required pre-processing in the app and (5) perform required regulatory checks. The pre-processing described in primarily consists of amalgamating separate room scans into one coherent floor-plan. Following preprocessing, the user can then check against regulations. For each of the implemented regulations, the user process is as follows:

Regulation 3.16 simultaneous evacuation: width of escape stairs. Firstly, the user positions the prototype with line of sight to the stairs – so the prototype can capture the width of the stairs and the presses the scan button. The user then uses the app to identifies (*via* touchscreen) the stairs in the room scan produced by the app. Finally, the user uses the app to provide other necessary information (the number of occupants of spaces). Finally, the app reports the width and indicates pass/fail.

Regulation 2.10 alternative escape routes. Firstly, the user positions the prototype with line of sight to all alternative escape routes – so the prototype can capture geometrical data about the room and escape routes. Once the scan is taken, the user uses the app to provide other necessary information (in this case if there is fire resisting construction present). The user then uses the app to identify (*via* touchscreen) the location of an escape route. The app then indicates *via* highlighted markers the location of compliant alternative escape routes. The user must then indicate the location of the actual alternative escape route. Then, finally, the app reports the angle and pass/fail.

This prototype was validated on an office building. In these trials, it proved capable and easy to operate. Actual measurements recorded are within 1 cm accuracy of hand based measurements in all cases. The demonstration regulation checks have proven successful in comparing the automatic results to those manually calculated. In total, it takes on average 1 min to scan a single space, meaning that a reasonable large building can be scanned in only a few hours. Despite this, however, there are several key considerations that must be discussed related to future adoption:

Line of sight. In order for the prototype to produce accurate results, it is necessary for is to have a clear, unobstructed line of sight to all wall elements. In many situations, it is difficult to ensure that a clear line of site to all wall elements is present. This finding largely dictated the inclusion of the monopod element of the prototype, as the adjustable height allowed it to be elevated to a height which in most buildings feature little obstructions.

Mirrors, windows, and doors. Perhaps the largest barrier to overcome in clean and accurate measurement is the noise and distortions created when the laser encounters reflective and glazed surfaces. In alignment with past literature, our scans found that the detection of reflective and refractive surfaces (i.e. mirrors and windows) was problematic and difficult to capture accurately. Mirrors create a reflection, whilst glass refracts incoming light, causing it to leave at a different location when it has passed through (Whelan et al. 2018).

Object detection – automating fire door inspections

This section describes the prototype developed for the automation of fire door inspection. The work in this section has largely targeted the fire safety guidance provided in *Approved Document B: Fire Safety,* complemented by BS EN ISO 7010 that defines the standard look of fire escape signage.

Currently, manual inspection of fire doors requires expertise in order to ensure it is done correctly. The key advantage of our prototype is that it embeds the rules within its implementation, meaning any individual that is competent to take photographs can gather the needed data.

The developed prototype implements an automated inspection method using object detection. The aim of this prototype is to be integrated as part of an inspection application, where the user would take a photograph of a fire door and input the relevant details regarding its location in a building, and the software would; (a) approve the signage or flag it up automatically as requiring replacement, and (b) detecting any damage, highlighting and subsequently flagging up for maintenance.

This demonstration utilises AI solutions to check for several components of a fire door from an image. This includes detecting the presence of the correct signage on the fire door and detecting damage to the door leaf itself, which may compromise the efficacy of the fire door. The technical details of both of the use cases are described in more detail in the following subsections.

For signage detection, the YOLOv5 algorithm was used to recognise the signage on fire doors. Preliminary investigations suggested that YOLOv5 was less error-prone than the main alternative, the Fast-R-CNN approach (Lin et al. 2017). The data set used to train the signage detection model included two hundred and thirteen unique images of fire doors gathered from catalogues and web searches. Pre-trained YOLOv3 weights and TensorFlow were used to optimise and train the deep learning algorithm for detection. Figure 2 shows the signage detection on sample images used.

For damage detection, the Mask-R-CNN algorithm is used to detect damage to fire doors. A VGG image annotation (VIA)

Figure 2. Illustration of some outputs of the signage/damage detection.

tool was adapted and used to create the segmented masks. One hundred and eighty-one training images were collected from web searches, and door damage was annotated using the VIA tool (Dutta and Zisserman 2019). In the foreground, polygons were used to mark the damages in the training images. The model was then trained using the COCO data set. Figure 2 shows the damage detection on sample images used.

Both of these prototypes were validated on unseen test data sets gathered online. These unseen test data sets were used to test each model, for each model the mAP (mean Average Precision) was calculated to evaluate the models. The results found that both methods performed with high accuracy and provided fast detection times. The model reached an mAP score between 0.9 and 1.0 for the signage and damage detection, which means the average proportion of the predictions that the model made correctly was around 90%.

Conclusion

This section has presented two proof of concept demonstrators; (a) fire escape route compliance and fire door inspections. Both demonstrators have been developed and validated. **Fire Door Inspections:** have been validated on unseen fire doors, conducted by gathering of fire doors only. The accuracy of the validation process showed the model was achieving between 90% and 100% accuracy. This validates that the prototype is able to conduct effective and accurate fire door inspections.

Fire escape route compliance. This was validated on an unseen office building. The scanner was deployed in the building and the extract building geometry was analysd and proved to be accurate to within 1 cm. Secondly, the actual results of the fire escape route checking provided by the software were then validated by a building control professional to determine their correctness.

Industry feedback

Following the development and technical validation of the prototypes, a validation was then conducted to understand: the industry attitudes towards automated compliance checking driven by automated data capture and if, according to the industry, the prototypes developed are technically feasible. This was delivered through an industry feedback event that was held (virtually). At the event, the concept and demonstrators were presented and feedback gathered.

Participants were invited from the members of the DCOM Network. This is a network of organisation interested in automated compliance checking. A total of 48 individuals attended broken down as follows; Building Control(6), Consultant(9), BIM Manager(5), Contractors(3), Assurance(3), Competency Management(2), Professional Bodies(2), Software Developers(3), Building Services Engineers (1), Design(5) and Academia (9). Individuals were invited from a variety of backgrounds, to generate holistic feedback.

Feedback was gathered by separating the participants into small groups, each with a research team, and conducting a small group discussion. The small group sessions are summarised in the following key points:

The need for whole-lifecycle compliance checking. Participants agreed that current processes engaged in by facilities' managers are labour-intensive, often involving pen and paper exercises to record compliance results. These prototypes have great potential to speed up this process and help avoid error. They also agreed that post Grenfell Tower, there is an increased need to evidence that assets conform with requirements.

General prototype feedback. Overall, participants felt that these prototypes meet this need, but time will tell whether this ripples through into effect policy/legal changes. Specifically, they found that the prototypes developed were definitely useful and applicable in the built environment, especially in use cases around building safety services and facilities management and t advantages presented were agreed with across the board. It was also mentioned that aspects of construction that are hidden (i.e. behind walls or underground) cannot be checked using these approaches.

Fire safety monitoring. The monitoring of fire safety was seen to be most relevant and important demonstrator, several organisations are currently considering options for on-site data collection – especially in relation to fire safety.

Measurement demonstrator. In terms of the measurement prototype, participants commented that there are currently LIDAR systems to do the initial measuring, but the linking method between measurement and design BIM models is missing or is not automated process.

Possible drawbacks/limitations. Currently, no one understands the business case to invest in the technology. This is a barrier. Additionally, formalized calibration is needed for any such instruments to reach commercial adoption. Finally, it was also commented that existing software solutions for compliance checking are not user-friendly and requires at least a minimum of code-programming knowledge. These prototypes are moving in the right direction of simplifying things.

Future work. Water usage, airflow rate, CO2 levels, movement, acoustic, waste, temperature, access control, air extraction, balcony loading, humidity, duty count of appliances, duty count of access points were identified as other possible use cases. It was also commented that the industry is activity seeking innovation to reduce duplication of effort and time. Finally, the participants also identified an extra user case of the scanner prototype – and indicated the measurement data collected could be converted into a simplified building model to driver other regulatory checks.

Conclusion

This paper has described foundational work in developing the concept of whole lifecycle compliance checking of built environment assets against construction regulations. This has answered the research question *How can whole life-cycle compliance checking of built assets make use of data capture and automated checking technologies?*

To answer, this research question, this study utilised two scenarios related to fire safety that are applied to the operational phase of a building's life cycle. The two scenarios are not exhaustive of all operational phase checks but demonstrate how data collection and automation can be applied to whole-lifecycle compliance checking as well as the overall validity of the concept itself.

The key contributions of this work have been;

- the analysis of how whole life-cycle compliance checking can be applied to the UK building regulations,
- the development of two whole-life-cycle compliance demonstrators and validating the performance and key advantages of these demonstrators.

In a practical sense, this paper paves the way for future exploration of the whole lifecycle compliance checking concept, having identified the technologies to be explored, the regulatory use cases that can be examined as well as verifying the feasibility of the overall approach.

This paper finds that automated compliance checking in the built environment can into the operational phase of a building's life-cycle, allowing the implementation of whole life-cycle compliance checking for certain aspects of construction regulations/standards. This is evidenced by; (a) the multiple feasible use cases identified from the UK regulations in Table 1, (b) the availability of existing technologies to implement solutions for these use cases and (c) the two demonstrators produced in Section 5 and the positive industry feedback received on them (Section 6).

Overall, these conclusions demonstrate the validity of the whole life-cycle compliance checking concept, but also highlight the need for further research into additional use cases of the technologies highlighted in this paper and new technologies that can be leveraged to perform compliance checking.

However, this research does have some limitations:

- The development of the prototype devices have only gone as far as early stage development. The technical feasibility of each approach has been verified, however, to fully validate each individual approach for full regulatory accuracy additional studies must be conducted across multiple demonstration buildings.
- Some candidate regulations summarised in Table 1 had no off the shelf hardware available and thus could not be explored in this research.
- The analysis of each prototype was limited to an initial subset of the regulations that it is capable of checking against. In order to conduct a full assessment, further studies must be conduct to validate prototypes across all applicable regulations

Building on these limitations, the following future research directions are proposed:

- This study used two scenarios related to fire safety that are applied to the operational phase of a building's life cycle. The two scenarios are not exhaustive of all operational phase checks but demonstrate the validity of checking in the operational phase. Other checks will have their nuances, but the validation of the concept of using off the shelf technologies such as LIDAR and thermography to enable operational phase checking is valuable.
- Further validation of each prototype and its applicability to additional regulations.
- Further use cases from the UK regulations (such as those suggested in 6) should be examined using the technologies suggest by this paper to determine their feasibility.
- The potential of aerial drones or similar approaches should be examined to determine if this approach provides a solution for access issues encountered in performing automated compliance checking during the operational phase.
- The survey of regulations should be extended from the UK to additional countries, ascertaining the applicability of this concept in multiple nations, and which aspects of checking are common, and which are nation specific
- For buildings with no existing BIM model, the concept of building a simplified version of a BIM model specifically for compliance checking should be explored. Such a simplified BIM model would contain less information than a standard model, enabling quicker and cheaper building of the model, but would still contain the information needed for regulatory checks as required by the building operator.

Even though this work has focused on the UK, the results are generalisable to other regulatory contexts. Specifically, while the regulation analysis utilised the UK regulations, the same general subdivision of regulations apply to many nations i.e. (1) fire safety, (2) accessibility, (3) building fabric performance and (4) building energy performance. Thus, while the detail of the regulatory findings are UK specific, the general understanding of how whole life-cycle compliance can be applied to regulations is generalisable. Furthermore, while the specific decision-making capability of the demonstrators are built against the UK regulations, the demonstrators themselves can be generalised to support the regulations of other nations.

It is our view that the concept of whole life-cycle compliance checking is increasingly important in the short term future as governments seek to better monitor and assure high risks elements of their built environment. In the UK, this is already being enacted *via* the Building Safety Bill. This process of whole life-cycle compliance becomes impractical and expensive when relying on solely manual inspections, so there is a key developing need for automated or semi-automated solutions in this area. The prototypes developed in this paper present the first steps along this route, and pave the way for both their future development and the development of prototype in new use cases tackling new regulations.

Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

Data underpinning the results presented here is available for the Cardiff University data repository at http://doi.org/10.17035/d.2024.0326523640.

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