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Automated compliance checking in healthcare building design

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ABSTRACT

Regulatory frameworks associated to building design are usually complex, representing extensive sets of requirements. For healthcare projects in the UK, this includes statutory and guidance documents. Existing research indicates that they contain subjective requirements, which challenge the practical adoption of automated compliance checking, leading to limited outcomes. This paper aims to propose recommendations for the adoption of automated compliance checking in the design of healthcare buildings. Design Science Research was used to gain a detailed understanding of how information from existing regulatory requirements affects automation, through an empirical study in the design of a primary healthcare facility. In this study, a previously proposed taxonomy was implemented and refined, resulting in the identification of different types of subjective requirements. Based on empirical data emerging from the research, a set of recommendations was proposed focusing on the revision of regulatory documents, as well as to aid designers implementing automated compliance in practice.

1. Introduction

Design solutions need to be assessed against the project scope and expected benefits. Assessment consists of identifying and uncovering inconsistencies between design and requirements, including regulatory constraints [18,60,82], before design is frozen or finalised. In the building design context, these cycles of analysis and evaluation improve design quality by ensuring that (a) stakeholder and clients' needs are fulfilled [37] and (b) design solutions are compliant to guidelines and statutory requirements [15,56]. Thereby, design assessment enables the elimination of errors and provides an opportunity to improve value generation [23,24,36].

The use of automation to support design compliance checking has been suggested as an important means to navigate through this process, and the literature highlights several potential benefits from it [18]. Automation allows connecting and coordinating different types of information in building models [10,40,42], and checking design compliance through a faster, more efficient and reliable process [18].

In fact, automated compliance checking is based on rule checking algorithms and has been a research topic for over 20 years. This led to the development of multiple approaches, models, frameworks, systems and programming languages (see Table 1). However, there has been limited success on the implementation of automated compliance checking in practice, as there are difficulties in dealing with myriad regulatory requirements [18,43] as well as limitations from existing technology to support this process [75].

Ensuring compliance is even more difficult in the healthcare design context. This is due to: (i) the complexity of healthcare projects, resulting from the variety of elements, systems and subsystems that dynamically interact [19,30,70,71]; (ii) the large amount of information involved in the healthcare design process [47,49] related to the diversity of requirements from design, construction and operation [7,30,84]; (iii) the frequent changes that happen during design [9,61]; (iv) the interaction between regulatory and clients' requirements, which can be conflicting, and evolve over time [40,41,74]; and (v) the large number and high complexity of existing regulatory documents, which have been developed through a piecemeal, and therefore uncoordinated approach especially in the UK, leading to a confusing mix of healthcare design statutory and guidance documents [31,51].

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Healthcare facilities aim to deliver health and social care so that people can have better access to services through high quality buildings. In the UK context, their design has been described as essential to improve services delivered to communities, having a direct impact on the health and wellbeing of patients and staff [11,26].

The use of automated checking in design has been suggested as fundamental to enhancing quality and to deal with the complexity associated with healthcare design [58,67]. The literature clearly indicates that manual approaches for building compliance checking may lead to inconsistencies and are prone to error [6,18,28,34,43,47,56,64,68,69,89,90].

Non-compliance to regulations and guidance might compromise the quality of the built environment and the quality of the services delivered within healthcare facilities – which, in turn, can impact on health outcomes [84]. Also, compliance issues may lead to delays in healthcare design, extra costs, as well as design rework and poor quality. Despite advances in existing research, there are still gaps in understanding the information content of guidance and statutory documents [75,78], which has led to difficulties in the practical implementation of automated solutions in this domain.

This paper proposes recommendations for the adoption of automated compliance checking in the design of healthcare facilities. It discusses the utilisation of digital tools aligned with process changes that are necessary to improve the future adoption of automation. More specifically, these recommendations aim to provide a structured approach which can simplify automated compliance checking.

Specific objectives include:

(i) test the utility and refine a taxonomy devised in a previous study [79] to classify requirements from statutory and guidance documents;
(ii) map quantitative, qualitative, objective and subjective requirements in a sample of UK healthcare statutory and guidance documents to identify opportunities and difficulties in the practical use of automated checking;
(iii) model a sample of requirements and rulesets in a case study project, using a commercially available tool (Solibri Model Checker);

Initially, this paper discusses the healthcare design regulatory framework in the UK. The paper then synthesises existing research in automated compliance and rule checking. Thereafter, the method adopted in the research is described. Results are presented, followed by the recommendations. Finally, an analysis of results is presented.

2. Healthcare design regulations in the UK

The National Health Service (NHS) Constitution commits the NHS to ensure that services are provided in a *"clean, safe, secure and suitable environment"* ([14], p. 7). Consequently, much emphasis has been given to the importance of design quality in the context of healthcare facilities [31].

In the 1990s and 2000s, Public Private Partnerships (PPP) were used to deliver healthcare facilities in the UK. The Private Finance Initiative (PFI)[1] was the most popular PPP model used by this government [2]. The Department of Health (DH) coordinated capital programme resulted in the prolific development of new standards and tools [2,51], which contributed to an evidence and experience base, as well as common benchmarks and standards presented in the Health Building Notes (HBNs) developed at the time [51]. DH assumed a central role in this process, being in charge of managing the relationships between public and private organisations [51]. This has been facilitated by the development of standards, design gateway reviews (e.g. OGC[2] gateway review process) and centralised procurement methods, such as the PFI, Local Improvement Finance Trust (LIFT) and Procure 21 (P21) [51].

This process has gradually modified the healthcare building design culture [31]. While PFI processes enabled innovation at first, they have led to multiple issues associated to financial constraints and lack of trust between healthcare planners, clinicians, architects and the PFI consortia, often leading to an adversarial design environment [31]. Furthermore, the focus on healthcare infrastructure has also changed in this context, shifting from the development of new buildings to upgrading existing assets. This was needed to reduce running costs, reshape existing buildings to enable modern service delivery and to improve standards [51]. Currently, ProCure21+[3] and ProCure 22[4] frameworks are the recommended procurement methods for publicly funded healthcare capital projects over £1 million.

Health Building Notes (HBNs) and Health Technical Memoranda (HTMs) play an important role in supporting healthcare building design decision-making in the UK. They should be understood as best practice guidance standards, providing *"essential information on how to comply with the statutory and policy framework around the assurance of estates and facilities"* ([12], p. 2).

HBNs focus on planning and designing both new and existing healthcare facilities, providing information to support briefing and design [12]. HTMs give comprehensive advice and guidance on the design, installation and operation of specialised facilities and engineering technology in buildings used to deliver healthcare [13]. The focus of HTMs is on healthcare-specific elements of standards, policies and established best practice. The legal framework bounding these documents is presented in Fig. 1, based on the contents from Health Building Note 00–01 [12].

The 'UK healthcare design regulatory framework' can be described as: (a) design guidance provided by the Department of Health (HBNs and HTMs); and (b) statutory documents, such as legislation, approved documents of building regulations,[5] provided by the Ministry of Housing, Communities & Local Government. It is important to highlight that some of these documents are devolved to individual nations in the UK. Different regulatory design requirements help achieving specific quality outcomes [51]. Hence, detailed checking of designs against this type of documents is essential [56].

The following policy challenges in the UK healthcare regulatory context have been identified by Mills et al. [51] through workshops involving the Healthcare Infrastructure Regulatory System and Department of Health Standards and Guidance Review:

- There is a complex mix of statutory and guidance documents, which creates a confusing regulatory environment;
- The majority of standards has evolved over time, leading to a convoluted definition of risks and lack of clarity on liabilities and

[1] "PFI enables the private partner to build a facility to the output specifications agreed to with the public agency, operate the facility for a specified time period under a contract or franchise with the public sector client and then transfer the facility to the latter party when the contract expires." ([2], p. 602).

[2] The Office of Government Commerce (OGC) was part of the government treasury and produced guidance about best practice in procurement and project management, highlighting preferred government procurement routes and support through the OGC Gateway Review process.

[3] The ProCure21+ National Framework consists of an agreement with the six Principal Supply Chain Partners (PSCPs) and their supply chains for capital investment construction schemes. More information on https://procure21plus.nhs.uk/about/

[4] The ProCure22 consists of a construction procurement framework for the development and delivery of NHS and Social Care capital schemes in England, governed by NHS England and NHS Improvement. More information on https://procure22.nhs.uk

[5] There are changes yet to be applied to The Building Regulations. The full list of updates to be incorporated into the documents is available on https://www.legislation.gov.uk/uksi/2010/2214/introduction

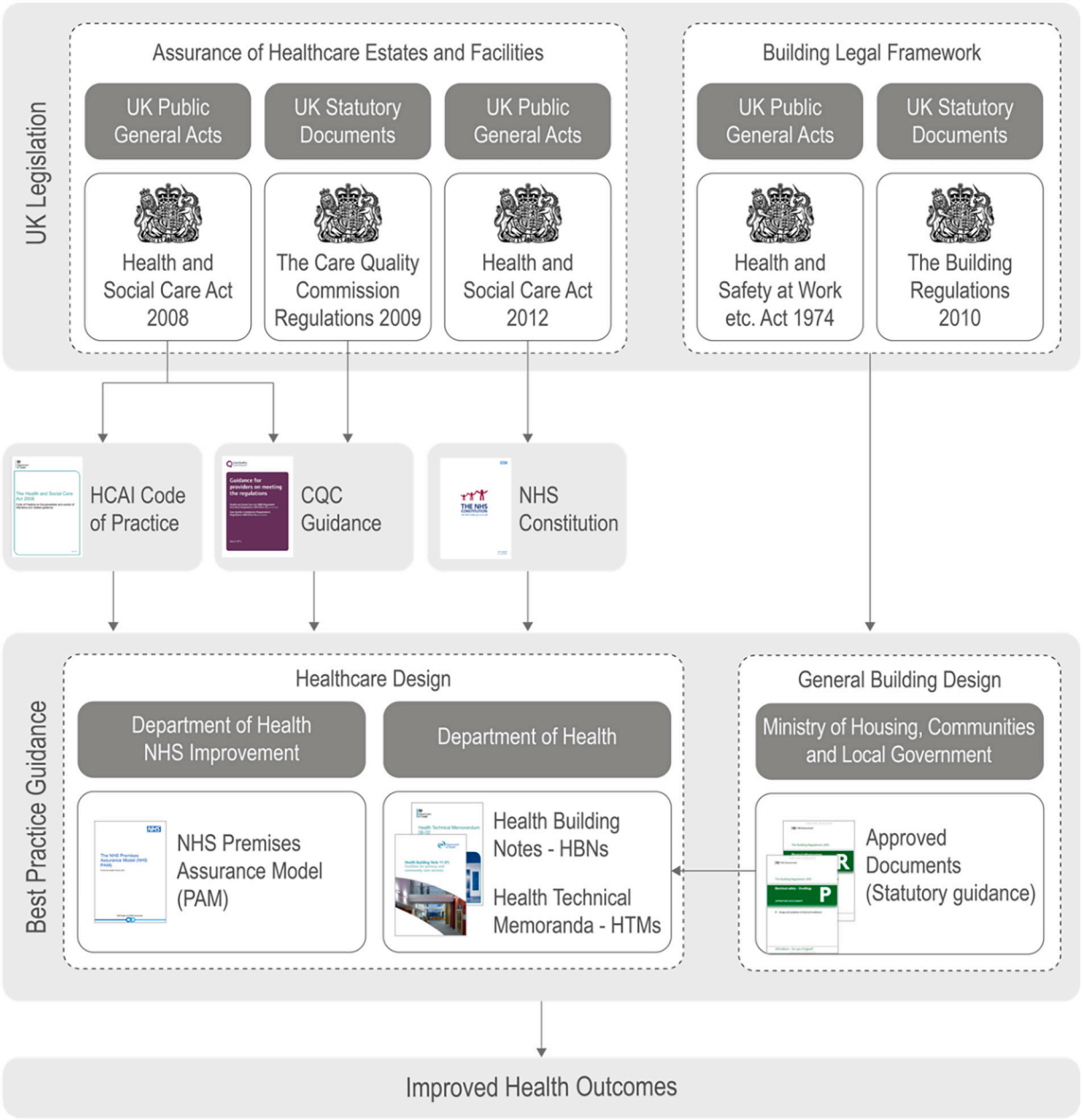

Fig. 1. Guidance documents and the legislative framework in the UK, based on HBN 00–01 [12].

compliance responsibilities. This also leads to gaps and overlaps that may impact design quality;
- Changes in regulations have occurred with little understanding of estates and facilities quality and standards;
- No single healthcare infrastructure quality and safety tool to drive compliance, assurance and prevention exists.

Hignett and Lu [31] also highlight the complexity arising from the uncoordinated regulatory framework in this context. They identified that review panels can stifle design, and the use of guidance documents is perceived as a constraint, with non-compliances having a great impact in the project and tendering process. Mills et al. [51] further argue that the approach to standards and guidance currently in place to direct healthcare building design quality improvement lacks rigour. This context makes efforts to enable some level of automated compliance checking difficult to be achieved in practice.

3. Regulatory requirements and automated compliance checking

Building codes, regulations, design guidance and other statutory documents are written in natural language, and have been developed, read, interpreted and used by people [18,52]. Hence, a large number of complex expressions are used to describe requirements. At times, these sentences contain multiple layers of implicit knowledge. Fenves et al. [20] argue that regulatory requirements are indeterminate by nature due to their open-text elements, which can hardly be applied in automated scenarios. This is because (a) they are context-dependent, requiring a considerable degree of interpretation to be judged [20]; and (b) have an open-ended number of senses, which, in turn, implies vagueness and ambiguity [52]. The above makes the process of translating such sentences for use in automated approaches challenging [43].

Even though issues related to requirements' subjectivity have been identified many years ago by e.g. Fenves et al. [20], they have been

reported by recent research still as a key challenge. Solihin and Eastman [78] stated that using regulatory documents as an input for automated rule processing is a very complex endeavour due to the language interpretation issue, which should be able to capture human knowledge in a formalised way to ensure completeness and precision. One of the main difficulties reported by existing research is in translating information from the regulatory framework, written using text, schedules, drawings, sketches and pictures, to computer-oriented logic expressions [43], without losing meaning. It has been the motivation of many efforts to structure and translate information from statutory and guidance documents for automated compliance checking over the years [75].

The above is observed not only in the healthcare building design context in the UK, but across many countries and in different design contexts, as evidenced by Table 1, which outlines the main developments reported in the literature in recent years. Publications are presented according to the type of outcome produced, their focus and target use, as well as their scope of development, testing, application and analysis. Countries associated to each publication scope are also presented, whereas in cases where information was not available, countries from the leading authors were included.

Existing research in automated compliance checking highlights diverse developments in technology and computation. They tend to

Table 1
Recent automated compliance checking developments.

Reference	Main type of development	Focus	Target use	Scope of development/testing/application/analysis	Country (scope)
[20]	Literature review	A	IDV	1977 ACI Building Code Requirements for Reinforced Concrete (ACI 1977)	USA
[85]	Approach	A	IDV	Software-based (IT)	Singapore
[18]	Framework	A	IDV; RA	CORENET; HITOS project - Norwegian Statsbygg; Australian Building Codes; US International Code Council; General Services Administration (GSA-US)	Singapore, Norway, Australia, USA
[53]	System	A	D; IDV	Structural engineering design	N/A (USA)[a]
[87]	Approach	A	RA	C3R (Conformance Checking in Construction — Reasoning) prototype	France
[83]	Approach	A	D; IDV	Building envelope design	Canada
[86]	Method	A	RA	C3R (Conformance Checking in Construction — Reasoning) prototype	France
[4]	Analysis/Approach	SA	D; IDV	Building energy performance (BEP) simulation	N/A (USA)
[62]	Overview	A	IDV; RA	Acoustic performance (test case) - acoustic performance regulations	Belgium (and EU)
[21,22]	Project	A	RA	Legal requirements - accessibility and egress	USA
[54]	Framework	A	RA	Legal requirements - automated code compliance checking	USA
[52]	Overview	A	–	–	N/A (USA)
[55]	Overview	A	–	Structural BIM	N/A (USA)
[90]	Model	A	CQI	Construction quality inspection	China
[1]	Literature review	A	–	Semantic web	N/A (UK)
[15]	Literature review	A; SA	–	AEC industry in New Zealand	New Zealand
[56]	Literature review	A	–	–	N/A (USA)
[35]	Framework	A	IDV	Energy performance analysis	N/A (Germany)
[44]	Programming Language	A	IDV; RA	Spatial objects, group of spaces, circulation paths, their properties, and relations.	N/A (Republic of Korea/ USA)
[5]	Approach	A	IDV; RA	BREEAM and code for sustainable homes	UK
[64]	Overview	A	IDV; RA	–	N/A (Belgium, USA)
[77]	Classification	A	IDV; RA	General use for classification	N/A (USA)
[88]	Method	A	RA	International Building Code 2009	USA
[16]	Overview	A	RA	New Zealand Building Code (NZBC)	New Zealand
[32]	Framework	A	IDV; RA	BIM based model checking concepts	N/A (Norway)
[34]	Approach	A	IDV; RA	Constructability review (focusing on reinforced concrete structural elements)	United States
[43]	Approach	A	RA; SD	Korean Building Act	Republic of Korea
[49]	Programming Language	A; M	D	Design brief	Australia
[59]	Programming Language	A	RA	Korean Building Act	Republic of Korea
[68,69]	Programming Language	A; SA	IDV	German fire code DIN 18232–2; Korean Building Act	Germany, Republic of Korea
[78]	Approach	A	SD	Building rules	USA
[47]	Model	A	SD; PM	İzmir Municipality Housing and Zoning Code (IMHZCode)	Turkey
[63]	Overview	A	SD	SPARQL and SPIN; EYE and N3Logic; SWRL rules with a semantic graph database	N/A (Belgium)
[65]	Literature review	A	SD	Semantic web technologies	N/A (Belgium)
[89]	Schema	A	SD	Quantitative requirements IBC 2009 Chapter 19; two-story duplex apartment test case in two ways, using perfect information and imperfect information	USA
[80]	Overview	A; SA; M	D; IDV; RA	Healthcare - emergency sector of hospital design	Brazil
[25]	Model	A	IDV; RA	Business rules and requirements; nuclear power plant engineering	France
[27]	Approach	A; SA	IDV; RA	International Residential Code; guidelines for design and construction of hospital and health care facilities	USA
[39]	Programming Language	A	IDV; RA	Korean Building Act	Republic of Korea
[45]	System	A	IDV; RA	China Code of Building Fire Protection; school project	China
[57]	Framework	A; SA	IDV; RA	FBC 2017- Residential; two-story building	USA
[72]	Model	A; SA	P	Site layout planning	Germany
[81]	Overview	A; SA; M	IDV; RA	Healthcare - primary care design	UK
[76]	Overview	A	IDV; RA; SD	–	N/A (Singapore, New Zealand, USA)

A – Automated; SA – Semi-automated; M – Manual; IDV – Internal Design Validation; D – Design process; RA – Regulatory Approval; SD – Software Development; PM – Policy Making; CQI – Construction Quality Inspection; P – Production.

[a] N/A relates to cases where information was not available. Countries from the leading authors were indicated.

focus on very specific contexts, as indicated by Table 1, which compromises their widespread use [39,57]. Table 1 also indicates that most developments focus on the complete automation of design checking, not considering the partial use of automation alongside human inputs (e.g. semi-automated or hybrid approaches). Additionally, the majority of research was developed to (i) support internal design validation or the regulatory approval process; or (ii) provide some degree of software development.

Identifying the nature of regulations and the hierarchical requirements information is essential to enable the implementation of a degree of automation in the design assessment process [47]. Solihin and Eastman [78] highlighted that analysing regulatory requirements is a very important step to enable automation. Clearly identifying requirements that cannot be automated is also essential to realise the limitations of automated systems [55]. Such analysis needs to be conducted by experts and could be facilitated by using classifications to enable grouping elements in different classes, according to their very own characteristics, such as a taxonomy [32].

Existing research proposed a taxonomy to classify regulatory requirements focused on automated compliance checking, based on the Brazilian healthcare design framework [79]. This taxonomy consists of four classification elements:

(1) the **nature** of requirements, supporting the identification of the type of information i.e. qualitative, quantitative, or ambiguous (where it is not possible to identify the predominance of qualitative or quantitative information).
(2) **translation to logic rule** describes whether a requirement can be re-written as a logic expression. This step is based on the Atomic Sentence (AS), "a type of declarative sentence that is either true or false" ([59], p. 425), in which formalised sentences originate the functional codified requirements according to a S (subject) + V (verb) + O (object) structure. These sentences are based on two key elements: (i) content (related to their meaning, e.g. object information, properties, location) and (ii) condition (usually associated to the verb-object (VO) in the sentence, defining which criteria the content must fulfil) [43]. This classification follows the semantic-based process described by Lee et al. [43], in order to obtain an Arithmetic Logic Unit (ALU). It does not rely on specific software constraints (e.g. rule modelling in Solibri Model Checker), as it only depends on the requirements' logical structure.
(3) **element** represents a 3D model object, expressing its relationship to regulatory requirements. This element of the taxonomy is based on the main types of objects used in building models, such as Furniture, Fixture and Equipment (FF&E) and Space. It links requirements to 3D objects, evidencing elements and information that need to be defined and modelled with precision, hence consisting of an important element of the taxonomy.
(4) **classes of parametric rule** from [77], i.e. requirements that can be translated into logical rules are classified in classes 1 to 4: (1) Class 1 — rules that require a single or a small amount of explicit data; (2) Class 2 — rules that require simple derived attribute values; (3) Class 3 — rules that require extended data structure; and (4) Class 4 — rules that require a "proof of solution". These classes represent the degree of logical complexity associated to requirements data structure, from both the building model and the rule sentence perspectives. Thus, Class 1 represent rules with low degree of complexity, while Class 4 represents the highest rule complexity.

One key element in this classification consists of understanding content and conditions included in the sentences [59], and whether they can be expressed under a computer-readable format, according to a logical rule structure [39]. Additionally, classifying the content of guidance and statutory documents can also support the identification of relationships between different requirements [47], as well as relationships between similar requirements described in different documents, which might enable the development of databases to feed into automated systems.

Despite the complexity of the healthcare design regulatory framework, there is a considerable part of the requirements that is explicit and prescriptive, such as design parameters, mathematical equations and dimensional constraints [16]. Such objective requirements have been considered in existing research efforts (e.g. [18]), and there are substantial benefits to be achieved in practice when used in automated compliance checking. Macit İlal and Günaydın [47] discuss that research efforts are still needed to deal with the less explicit or more abstract regulatory requirements. This can also be identified as a gap in the taxonomy proposed by Soliman-Junior et al. [79], which does not include any classification and analysis related to objective and subjective requirements.

4. Research method

Design Science Research (DSR) is the methodological approach adopted in this investigation. DSR has a prescriptive character and is used to address practical problems with theoretical relevance through the development of artefacts [29,38,46]. DSR was considered suitable for this research as the research problem is focused on the need to enable automation to improve healthcare design compliance checking. The artefacts refined and developed in the research are (i) a taxonomy used to classify information from regulatory requirements, and (ii) recommendations for the adoption of automated compliance checking in the design of healthcare facilities.

4.1. Research design

This investigation was divided into three phases: (i) understanding of the problem; (ii) development of the artefacts; and (iii) analysis and reflection, which are the typical stages of a DSR research project, as suggested by Holmström et al. [33]. Several learning cycles were undertaken due to the iterative nature of this research approach. One empirical study in the design of a Primary Healthcare Centre (PHC) was conducted in collaboration with an institution responsible for primary healthcare buildings across England.

The planned PHC will be located in the West Midlands and will replace temporary facilities, serving a list of 10,000 local patients. This project demonstrated close fitness and relevance to the research and was chosen because: (i) the PHC was conceived as a test bed from the owners' perspective, aiming to assess innovative approaches for healthcare infrastructure delivery, which introduced multiple challenges to design, increasing the project complexity (i.e. BIM and digital design compliance, use of the passive house approach, and modular offsite construction); (ii) the number of regulatory implications in this project included both objective and subjective requirements; (iii) the team undertaking the project had significant experience and therefore would benefit the research due to their expertise; and (iv) the project was at an early stage of development when the collaboration started, providing an opportunity to support all stages of the research.

A schematic representation of the research design is presented in Fig. 2, including its phases, main activities, sources of evidence, and the research artefacts according to their implementation, refinement and development (further details on Sections 5.1, 6.3 and 6.4).

Phase 1 focused on understanding regulatory requirements in the healthcare context. It included the identification of statutory and guidance documents to be analysed, and mapping the requirements embedded in those documents. Phase 2 was characterised by the construction of the artefacts. Healthcare statutory and guidance documents were classified according to the requirements taxonomy proposed in a previous investigation [79]. During this phase, the taxonomy was implemented, assessed and refined. The strong iteration between Phase 2 and Phase 3 allowed refining the artefacts through learning cycles, which also enabled reflecting upon practical and theoretical implications.

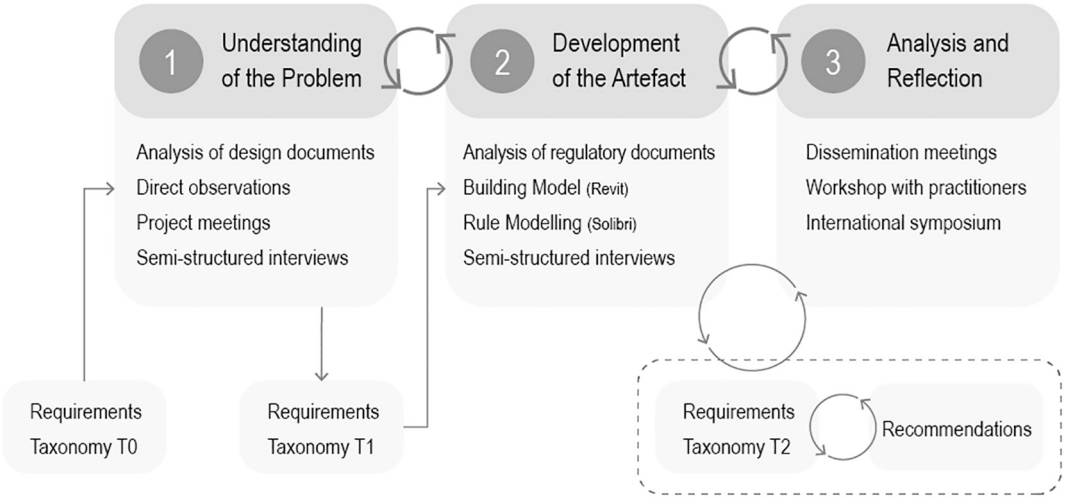

Fig. 2. Research design.

4.1.1. Sources of evidence

The main sources of evidence of this research are presented in Table 2. Semi-structured interviews were carried out with practitioners and members of the Higher Education. They were voice recorded, transcribed and adhered to a semi-structured interview protocol including: (i) context and key characteristics of healthcare projects; (ii) requirements management; and (iii) automation in the design process. Immediately after each interview, interviewers' notes and insights were incorporated into a database, complementing transcriptions and creating a comprehensive repository of information.

The documents analysed during the research correspond to both statutory and guidance elements of the healthcare framework, but also relevant design documents and reports. Dissemination meetings, workshop and symposium served as an opportunity to present research findings and discuss their outcomes.

Table 2
Sources of evidence.

Source of evidence	Description	Participants	Research phase		
			1	2	3
Semi-structured Interview	Healthcare Estates (Management and Facilities Services)	1	X		
Semi-structured Interview	Higher Education (Design Professor)	1		X	
Semi-structured Interview	Healthcare Design/Practitioner (Healthcare Architects A)	1	X	X	
Semi-structured Interview	Higher Education (Civil Engineering Professor)	1	X		
Semi-structured Interview	Healthcare Design/Practitioner (Healthcare Architects B)	2	X	X	
Semi-structured Interview	Higher Education (Requirements Management and BIM Professor)	1		X	
Semi-structured Interview	Healthcare Design/Practitioner (Healthcare Architects C)	1		X	X
Analysis of Documents	Analysis of 5 documents from the UK framework HBNs, HTMs and Building Regulations	N/A		X	X
Analysis of Documents	Analysis of design documents (2D plans, 3D models, operational process descriptions and assessment reports)	N/A	X	X	
Dissemination Meeting	Dissemination meeting with PHC stakeholders	8		X	X
Workshop	Presentation of research findings (client representatives, designers, software developers and policy makers)	26		X	X
Dissemination Meeting	Dissemination meeting with national healthcare chief executives	11		X	X
Symposium	Presentation of research findings and discussion (practitioners and leading international researchers)	28			X

4.1.2. Analysis of regulatory requirements

The choice of documents to be analysed was based on interviews, aiming to include the most relevant documents for the primary healthcare building context. Client representatives indicated key statutory and guidance documents according to their perspective, which have been prioritised in the research. The five analysed documents are (Fig. 3): (a) Health Building Note 11–01 – Facilities for primary and community care services; (b) Health Building Note 00–01 – General design guidance for healthcare buildings; (c) Health Building Note 00–03 – Clinical and clinical support spaces; (d) Health Technical Memoranda 07–07 – Sustainable health and social care buildings; and (e) Building Regulation – Access to and use of buildings – Volume 2: Buildings other than dwellings.

Requirements were classified by using the taxonomy, and later stored in a database. As three researchers were involved in the classification process, a systematic protocol and classification guidelines with examples were developed to ensure quality and consistency. To mitigate the risk of misinterpretation, all researchers involved in the tasks of identifying, analysing and classifying requirements had the same training at the beginning of the process. Moreover, researchers were assigned to adjacent workstations in the same office, supporting constant interaction and discussion of emerging issues. Furthermore, all classified requirements have been reviewed by the same researcher multiple times during and at the end of the classification process, ensuring prompt feedback and that consistent and appropriate classifications were adopted. This process supported the refinement of the taxonomy and the classification protocol.

4.1.3. Rule modelling

Rule modelling was performed in the case study (PHC) using Solibri Model Checker® (SMC) to test automated rule checking, including a sample of requirements from HBN 11–01. This sample was defined following (i) key requirements prioritised by the company collaborating in the study and (ii) relevance of specific types of requirements considering their coverage and scope in HBN 11–01. These are further described in Section 5.3.

Fig. 3. Analysed documents.

SMC was chosen for this test because it is currently the only standalone commercial application focused on automated rule checking supported by open formats (e.g. IFC) [75]; while HBN 11–01 consists of a key document for the design of primary healthcare facilities. The aim of the test was to assess the utility of the taxonomy, considering requirements classified as possible to translate to logic rules. Codified requirements were inserted in the software interface through the *"ruleset manager"*, with rules modelled according to the software predefined set of rules. The sample of classified requirements was inserted in SMC, translated, modelled and checked against the PHC building model, following the major steps proposed by Eastman et al. [18].

5. Results

Fig. 4 defines key constructs used in the research. Statutory and guidance documents represent the healthcare regulatory framework. Components are items within each of these documents, containing none, one or multiple requirements, as different parts of the sentence or diagrams might relate to different attributes and functions of the built environment. Requirements are the elements itemised and classified in this research according to the taxonomy. For traceability reasons, each requirement has been catalogued using a unique identifier (ID) e.g. 11.01.5.19.1. Table 3 describes how many components were identified in each of the analysed documents, and how many requirements derived from those. From this table, there is evidence that not all information included in the documents lead to requirements, as well as the differences on the number of requirements on each document. This is highlighted by e.g. HBN 00–03, consisting of 1872 requirements, whereas HTM 07–07 includes only 130 requirements. The detailed analysis of regulatory requirements is presented in Section 5.2.

5.1. Requirements taxonomy

The purpose of the requirements taxonomy is to enable a structured process of analysis and classification of information from regulatory

Table 3
Number of identified requirements.

Statutory and guidance documents	Components	Components that contain requirements	Requirements
HBN 11–01	460	317	782
HBN 00–01	412	324	576
HBN 00–03	641	572	1872
HTM 07–07	477	85	130
BR M2	157	134	456

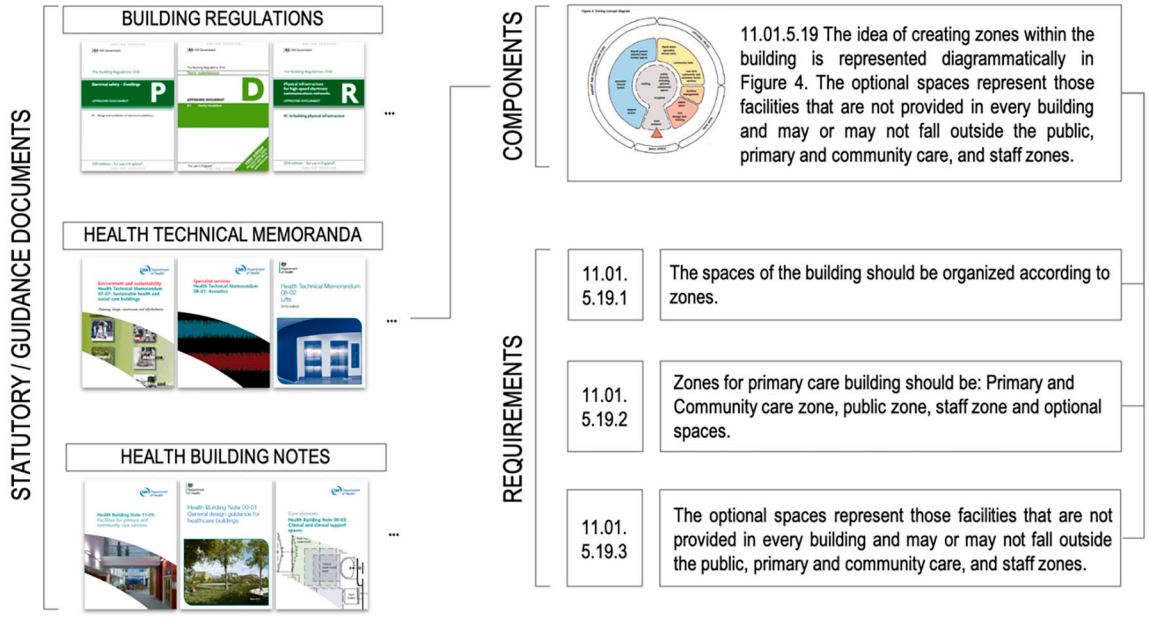

Fig. 4. Statutory and guidance documents, components and requirements.

documents. An early version of this taxonomy (T0) was presented in Section 3, based on previous work [79]. Originally, the taxonomy consisted of four elements (T0) (i.e. nature, translation to logic rule, element, and classes of parametric rule). It was implemented, assessed and refined (T1) is this research study, and two classification elements were added (T1): accuracy and referencing.

(i) **accuracy**: helps to identify whether requirements can be classified as objective or subjective. From the software engineering context, objective requirements are based on factual information [3] and their compliance can be assessed objectively [66], not depending on human interpretation. Alternatively, subjective requirements usually include personal feelings, views, emotions or beliefs [3], being subject to different opinions from experts [66], thereby depending on human reasoning and knowledge to be understood and assessed.
(ii) **referencing:** it is related to whether requirements in one document refer to other documents or databases. Referencing is not a classification on its own right, but it informs about links between requirements across diverse regulatory frameworks and other documents.

5.2. Regulatory requirements taxonomy analysis

The UK healthcare design regulatory framework currently includes approximately 108 documents, i.e. (a) 37 Health Building Notes (HBNs) and 52 Health Technical Memoranda (HTMs); and (b) 19 Building Regulations. The five documents analysed in this research study correspond to approximately 5% of the overall framework. Fig. 5 summarises key quantitative results of applying the taxonomy, presenting individual results per analysed document as well as an overall analysis. Table 4 includes a list of requirements and their classification according to the taxonomy T1. They are both used to illustrate findings discussed in subsequent sections.

5.2.1. Nature of requirements

In the five analysed documents, most requirements are qualitative (63%), which means they contain information which is not quantifiable, numerical, nor rely on measurements. From the remaining requirements, 35% are quantitative and 2% are ambiguous. It is important to highlight that ambiguous requirements were only identified in HBN 00–03 and were represented only in this diagram in Fig. 5. The documents have most of the requirements classified as qualitative, with the exception of HBN 00–03, in which 54% of requirements are quantitative.

5.2.2. Accuracy

Requirements in the analysed documents are 49.7% subjective whilst 50.3% are objective. HBN 00–03 has the majority of objective requirements. In contrast, most of HBN 00–01 contains subjective information, which demands a considerable level of human interpretation for consideration in the design process. This document presents general guidance for healthcare design, often expressed through conceptual diagrams and abstract relationships. As observed in Fig. 5, it is important to highlight that while most of the quantitative requirements are objective (97%), qualitative requirements are both objective (26%) and subjective (74%).

5.2.3. Translation to logic rule

Across the analysed documents, 53% of requirements cannot be transformed into a logical rule sentence. However, this is not the case in HBN 00–03 and HBN 11–01. HBN 00–03 has a high number of quantitative requirements, while HBN 11–01 is mostly qualitative. Despite differences in their nature, as seen in Fig. 5, both HBN 00–03 and HBN 11–01 have a significant number of objective requirements, which might evidence a relationship between accuracy and the possibility of translation to logic rules.

The above is also suggested in Table 4, considering that requirements classified as 'No' are also subjective. In this case, the sentence content or condition cannot be directly identified to formalise the logic rule without human interpretation. For requirements classified as 'Yes', for instance: 'Automatic movement-detected lighting should be considered in toilets and washrooms'. The elements of the logic sentence are: [*Automatic movement-detected lighting*: subject] – [*should be considered in*: verb] – [*toilets and washrooms*: object]. According to the AS structure (as described in Section 3), whereas the content refers to the subject, the condition is related to the verb-object. The logic sentence could then be used to obtain an ALU, following the steps proposed by Lee et al. [43].

5.2.4. Classes of parametric rule

Requirements that could be translated to logic rules, i.e. 1801 requirements (Fig. 5), were analysed according to their internal logical complexity using the classes of parametric rules developed by Solihin and Eastman [77]. Results indicate that 99% of these requirements belong either to Class 1 or 2 (Table 5). They indicate a high tendency of using automated rule checking approaches for these requirements, as Class 1 and 2 represent the cases of low to medium logic complexity, which is favourable for automation.

5.2.5. Elements

It was not possible to draw a direct relationship to an object in the building model for every analysed requirement. This factor is critical to automated compliance checking, since rule checking depends on relationship between objects, their properties and parameters. Across the five documents, 2601 relationships were identified. Most of them are related to 'Furniture, Fixture & Equipment' (55.4%), which include mainly healthcare furniture and medical equipment, and 'Space' (36.8%); followed by 'MEP' (4.8%), 'Door' (0.9%) and 'Remaining' (2.1%), which includes other elements e.g. Wall, Lift, Window and Floor. Table 6 includes examples of requirements and their classification. From a design perspective, these consists of key elements which should be prioritised while developing a building model to be used for automated compliance checking purposes.

5.2.6. Referencing

As the documents were analysed, referencing to standards and other documents was mapped. Usually, these documents refer back to different types of publications, including HBNs and HTMs, building regulations, scientific publications and other NHS documents. In the five documents, 158 different publications were referred to 385 times. Overall, the highest referencing is to HBN 00–01 (167 references), followed by HBN 11–01 (139 references) and HBN 00–03 (73 references). In terms of referencing, these findings were expected, as HBN 00–01 refers to general design guidance for healthcare buildings, while HBN 11–01 is focused on the design of primary and community care facilities. Both documents are important considering the scope in which the empirical study was developed, hence their highest referencing.

Furthermore, HBN 11–01 has self-referenced itself 18 times (13% of references), meaning that across its extension there are multiple references to other sections and diagrams from the same document. HBN 00–01, was referenced 16 times in HBN 00–03 (22% of references), and the set of HBNs was referenced 12 times in HBN 00–01 (7% of references) (i.e. HBNs as the entire set of documents, not related to one specific document).

5.3. Application of Solibri model checker

In the test, 221 requirements from HBN 11–01 could be automatically verified by using Solibri Model Checker® (SMC). They represent 53% of the requirements that can be translated to logic rules (419) and 28% of all requirements from HBN 11–01 (782). In practice, a significant number of requirements could already be used in SMC, saving time for designers and prioritising their work. Conversely, this means that not all

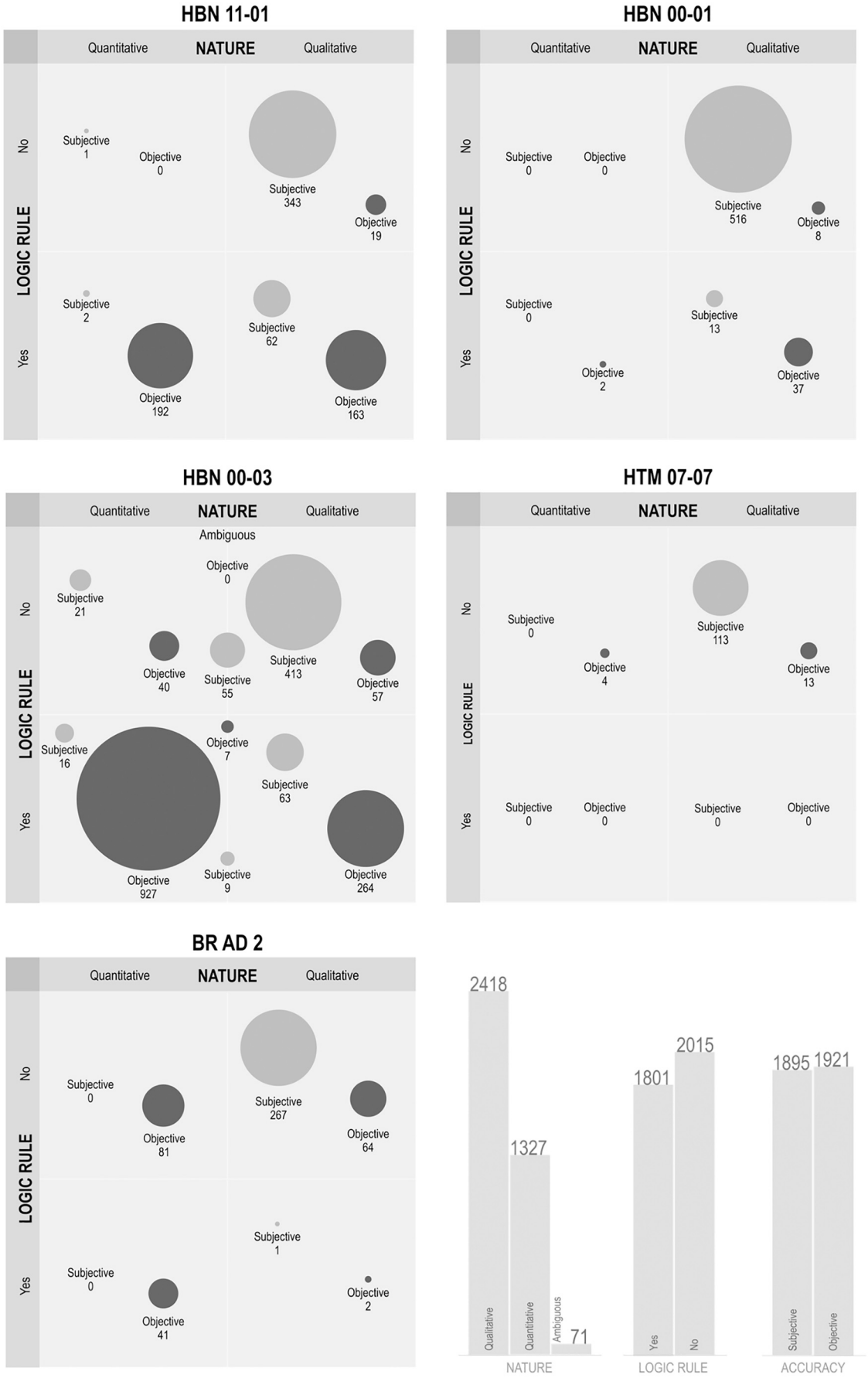

Fig. 5. Key quantitative results from the analysis of regulatory requirements.

Table 4
Examples of requirements and their classification according to the requirements taxonomy.

ID	Requirement	Classification				
		Nature	Accuracy	Logic rule	Class	Element
00.01.18.42.3	Adequate sound insulation needs to be considered between different rooms.	Qualitative	Subjective	No	–	–
00.03.07.01.1	A safe and secure children's play area should be provided off all main waiting areas.	Qualitative	Subjective	No	–	–
11.01.5.15.1	Staff rest rooms should provide good-quality environments to encourage their use and promote staff interaction.	Qualitative	Subjective	No	–	–
11.01.3.17.1	Experience and ergonomic analysis suggest the following room sizes provide a good fit for most generic rooms in primary and community care buildings: 8 m2, 12 m2, 16 m2, 32 m2.	Quantitative	Objective	Yes	C1	Space
11.01.3.19.22	The recommended size for a clean utility is 8 or 12 m2.	Quantitative	Objective	Yes	C1	Space
00.03.3.103.7	Examination/physical therapy room - Space on sides of couch (double-sided access) is 800 mm.	Quantitative	Objective	Yes	C1	FF&E
00.03.2.12.1	The preferred maximum number of beds in a multi-bed room is four.	Quantitative	Objective	Yes	C1	FF&E
00.01.16.03.1	Automatic movement-detected lighting should be considered in toilets and washrooms.	Qualitative	Objective	Yes	C1	MEP
00.03.3.04.1	Where separate consulting and examination rooms are provided, there should not be adjoining doors between adjacent examination rooms for reasons of patient privacy.	Qualitative	Objective	Yes	C1	Door
00.03.07.30.3	A children's play area in the waiting area should be based on 10% of the number of main waiting places and sized at 2 m^2 per child (with a minimum space for three children).	Quantitative	Objective	Yes	C2	Space
11.01.12.01.98	Staff rest and mini kitchen - allow 40% of staff to be in rest room at any one time.	Quantitative	Objective	Yes	C3	Space

Table 5
Detailed analysis of regulatory requirements – classes.

Class 1	Class 2	Class 3	Class 4
Rules that require a single or a small amount of explicit data	Rules that require simple derived attribute values	Rules that require extended data structure	Rules that require a "proof of solution"
94% (1695 requirements)	5% (82 requirements)	1% (24 requirements)	–

requirements that can be translated to a logic rule can feed SMC rules, due to software limitations and its native rule structures with limited flexibility.

Translating, modelling and verifying regulatory requirements in SMC partially assessed the utility of the taxonomy, in terms of translating requirements to logic rules. Three checking routines were tested according to the selection criteria presented in Section 4.1.3 and are further described below (the percentage refers to requirements that could be tested in SMC i.e. 221): (i) compliance of areas (47%); (ii) components (19%); and (iii) dimensions (2%). Despite dimensions covering a small share of requirements in HBN 11–01, corridor widths and ceiling heights were included in the checking sample. These requirements have been prioritised by the company involved in this investigation because they often result in non-compliances. Other types of requirements that could be translated to logic rules and used in SMC but have not been included in the checking sample are related to accessibility (3%), adjacency (4%), number (14%) and types of spaces (11%).

Floor area and ceiling height rules were successfully verified. The design verification automatically pointed out insufficient floor area for one treatment room and three consulting rooms. Another verified rule was the existence of components within spaces, such as equipment and furniture. It relates to FF&E and Space objects, which are the most common type of relationship between regulatory requirements and building models, as described in Section 5.2.5.

The use of a specific rule to check the width of corridors in SMC has been partially satisfactory. This verification flagged inconsistencies regarding doors in red (Fig. 6), which are perceived as inaccessible.

The above problem indicates a software limitation, which can be due to different reasons and is not clearly explained to the user because of the 'black-box effect' [43,78]. Despite SMC providing a predefined set of rules, which is flexible and customisable and allows fine tuning of some of the parameters by the user, the checking process is not transparent and fully accessible, making the identification of inconsistencies a convoluted trial and error process. In this example, the identified issues can be due to multiple reasons, such as: (i) doors appearing to be considered not as transition elements between spaces, but as obstacles in the corridor space; and (ii) the analysed corridors having irregular shapes, which can be conflicting to the pre-determined rule structure. In both cases, this information is not clearly presented to the user and was inferred by the researchers, hence the suggestion of a 'black-box'.

This issue in SMC introduces an inherited risk to the automated checking process reported in the research. The 'black-box effect' can also lead to false-compliant outcomes. This means that inconsistencies from multiple sources (e.g. rule definition, building model) could be unnoticed in the checking process due to its lack of transparency.

In previous studies [18,50], SMC was successfully used to verify requirements related to accessibility, properties of spaces and systems within specific areas. This research study confirms what is reported in existing literature, despite being limited to the types of requirements analysed, as well as the issue observed in spaces with irregular shapes (e.g. checking corridor widths).

Approximately half of the requirements initially indicated as translatable to logic rules could be incorporated to SMC. In fact, this also confirms previously literature findings [43,50,69,78], regarding the software limitations and the difficulties of translating regulatory requirements to feed SMC rules and other rule checking systems. Findings presented here suggest that SMC has a constraint in adapting its existing rule structures to the diversity of logical relationships identified in different documents. Furthermore, the lack of transparency related to rule checking in SMC might lead to inconsistent and false-compliant outcomes.

Table 6
Detailed analysis of regulatory requirements – elements.

FF&E	Space	MEP	Door	Remaining
55.4%	36.8%	4.8%	0.9%	2.1%
1442 requirements	957 requirements	125 requirements	24 requirements	53 requirements

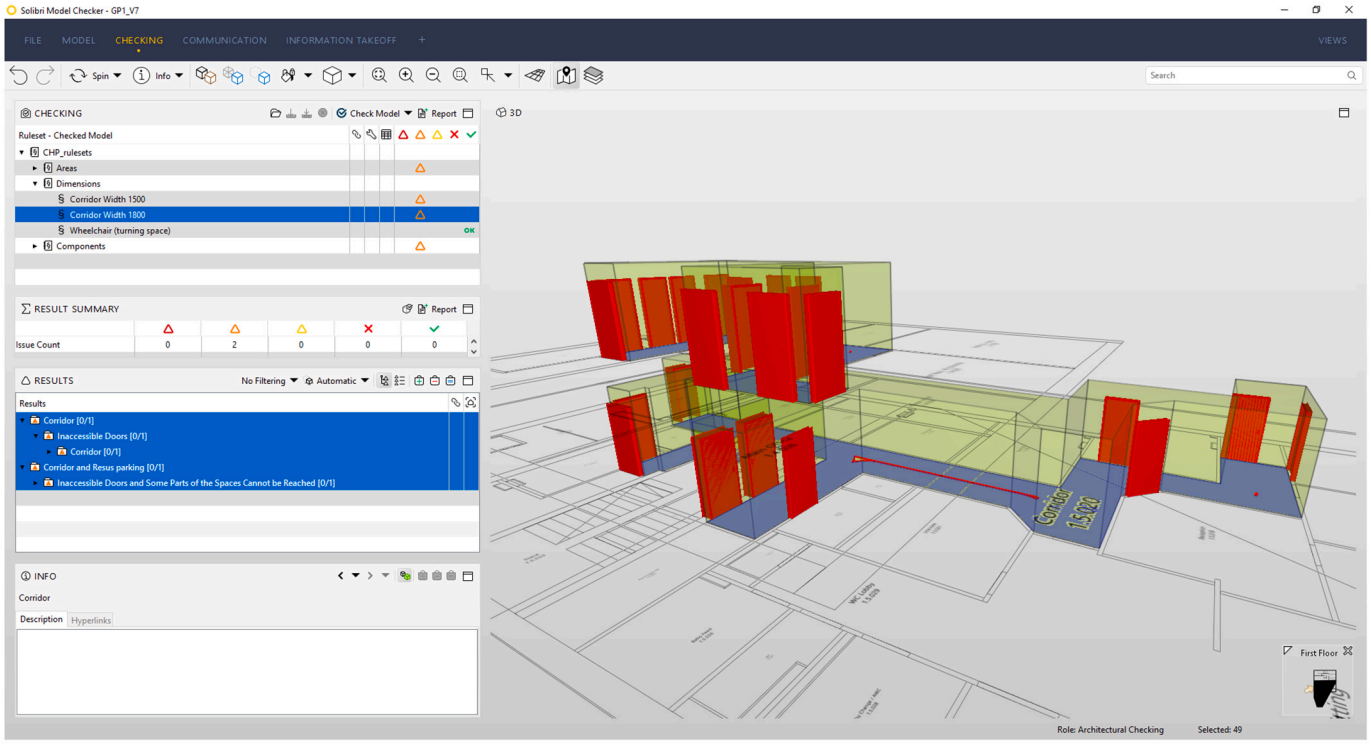

Fig. 6. Application of Solibri Model Checker – Example of checking corridor width.

5.4. Analysis of results

The quantitative analysis presented in Section 5.2 identified more than 3800 requirements. Most of these requirements are qualitative. In practice, this means they are presented as descriptions, definitions or inclusion and exclusion criteria, usually through words and pictures [73]. This is in contrast to quantitative requirements, which represent quantities, dimensions and other measurements, generally by using numbers or other discrete categories [73]. The classification also analysed requirements in terms of their accuracy (Section 5.2.2), indicating that half of the requirements are subjective. This means they depend on human interpretation to be transformed both into a design specification and verified in design proposals. Currently, it is not possible to use these requirements to feed directly into rulesets for automated compliance checking. It is important to understand accuracy as unrelated to nature: qualitative requirements are often assumed as subjective, but that is not necessarily the case, whereas quantitative requirements are generally assumed to be objective, but neither that is true [73], confirming findings highlighted in Section 5.2.

Findings reported on Section 5.2.3 demonstrate that 53% of the requirements could not be translated into a generic logic rule, needing further consideration mostly due to their subjectivity (further described in Sections 6.1 and 6.2). This step represents an initial reasoning on sentences being transformed to a logic structure, so they could be further used as checking rules in automated checking systems. The above suggests a potential relationship between accuracy and the possibility to translate requirements to logic rules. Sentence structuring has a direct impact on translating requirements into rules and attempts to review regulatory documents should aim to streamline this translation process and improve the use of automation.

When it comes to commercial software, this represents a lower number of requirements. Considering HBN 11–01, for instance, only 28% of its requirements could be used in SMC. Furthermore, 25% of requirements from this document can be represented as logic rules but could not be incorporated into SMC due to the software limitations, such as described in Section 5.3. In this case, requirements could be used to feed in-house checking routines based on their logical representation by using Visual Programming Language (VPL) tools, such as Dynamo and Grasshopper, as plug-ins to modelling tools.

Even though most of the identified requirements are difficult to feed into automated checking systems, some represent quantitative or objective information and clear logic relationships. Often, such requirements tend to be classified mostly as C1 and C2 [77], which is favourable to automation due to representing cases of low logical complexity.

Furthermore, over 10% of the identified requirements have cross-references to an external publication or other sources of information. This represents a great challenge for designers to ensure both statutory and guidance documents are followed, leading to compliant designs. It also provides evidence of the interrelated character of the healthcare building design framework in the UK, which makes automation difficult to be achieved in terms of compliance checking. This may be the case in other countries as well. In the Brazilian context, for instance, there is only one healthcare building design regulation [8], which has many references to other building regulations [79]. Nevertheless, further application of the taxonomy in different contexts is needed to identify whether this represents only an isolated situation, which is amplified by the convoluted regulatory framework in the UK.

The research demonstrates that despite difficulties, commercially available software like SMC can still support automated compliance checking for both quantitative and qualitative requirements with some limitations, as demonstrated in Section 5.3. Hence, existing software can be used to achieve partial automation in design compliance checking. This paper also highlights that analysing the information content from regulatory documents is essential to enable automated compliance checking, whereas requirements that cannot be automated should also be clearly identified [55].

Difficulties related to design creativity and the use of automated approaches in practice were highlighted by the interviewees. They might be due to the fact that existing research has tended to oversimplify real needs and overlook subjective requirements, which are key to creativity and fundamental to design. As previously discussed, subjectivity has been pointed out by literature as detrimental to design compliance checking

[21,77]. Thus, objective and subjective requirements need to be dealt with differently, i.e. automated rule checking can be used for quantitative and objective requirements, and hybrid or semi-automated support systems could be developed to deal with subjective requirements. In fact, existing research recognise the importance of semi-automated approaches as a transition towards complete automation [15,16,47]. Such importance was also identified as beneficial from the interviewees' perspective, but with a more permanent character rather than temporary.

6. Contributions of the research

From the evidence generated by this research, it is clear that subjectivity cannot simply be eliminated from the regulatory framework while it is key to enabling automation. Two types of subjectivity were identified in the regulatory framework: natural and artificial subjectivity. By understanding how subjectivity exists within regulatory requirements, a refined version of the taxonomy is proposed (T2), and a clear pathway to better address subjective requirements in automated compliance checking can be defined. The refined taxonomy consists of a key contribution of this research, which is presented in this section alongside recommendations, followed by a critical analysis of results.

6.1. Natural subjectivity

Natural subjectivity originates from abstract information included in requirements' definition, represented by abstract elements e.g. design flexibility. This type of requirement cannot be directly translated into an objective sentence and shaped into a logic rule without some level of human involvement and cognitive reasoning. Consequently, they cannot be checked through automated approaches. Abstract and intangible requirements need to be transformed into concrete attributes to enable its use in automation, and this is not a straightforward process, demanding expert knowledge and being prone to bias.

In practice, natural subjective requirements are part of the regulatory framework to support design decision-making without over constraining design solutions. They are used by designers, and interpreted through abductive processes, as part of decision making. Hence, natural subjective requirements represent a major barrier for the implementation of automated compliance checking. They demand careful consideration by policy makers creating or revising statutory and guidance documents. An unbalanced amount of natural subjectivity can either over constrain the design process or impede a degree of automation to be implemented in practice.

6.2. Artificial subjectivity

Artificial subjectivity is a consequence of poorly written statutory or guidance documents. Often, requirements are subjective not because they represent abstract and intangible information (i.e. natural subjectivity), but due to the way they are transformed into sentences and how these are grammatically written.

Artificial subjectivity could be eliminated by making better use of objective, precise, clear, non-redundant and independent sentences. The existence of artificial subjectivity further highlights the need for revisions on the existing healthcare design regulatory framework. Examples of natural and artificial subjective requirements are presented in Table 7, followed by suggestions on how to improve clarity, precision, definition and objectivity of sentence structuring whenever possible. In this table, the key elements which justify either natural or artificial subjectivity are in bold. As an example, **adequate sound insulation** is classified as artificial subjective because sound consists of a measurable parameter, with specific acceptable levels being objectively defined in HTM 08–01. By contrast, **safe and secure** leads to a natural subjective requirement because these are abstract elements which cannot be directly measured, relying on human interpretation to be translated to concrete attributes.

Table 7
Examples of natural and artificial subjective requirements.

ID	Requirement	Classification
00.03.07.01.1	A **safe and secure** children's play area should be provided off all main waiting areas.	Natural Subjective
11.01.3.01.1	Because the mix and range of services to be delivered from primary and community care buildings can change over time, it is important that the accommodation is **flexible and adaptable**. *[followed by a list of strategies at an abstract level]*	Natural Subjective
11.01.6.16.1	The layout of waiting areas should be **flexible enough** to accommodate patient flow at peak times. *Suggestion to improve sentence structuring:* 'flexible enough' is a convoluted expression which should be better defined. Flexible enough results in artificial subjectivity because of how this expression is presented to designers; what is flexible enough? After consideration, emerging requirements associated to this example might still be classified as natural subjective, due to involving an abstract element (i.e. flexibility). Careful consideration is needed.	Artificial Subjective
00.01.18.42.3	**Adequate sound insulation** needs to be considered between different rooms. *Suggestion to improve sentence structuring:* 'adequate sound insulation' could be defined objectively based on insulation components and materials' properties. Reference to levels of accepted noise in decibel (dB) could be provided to define what is adequate in this situation, as in HTM 08–01. Furthermore, this could be understood as a duplicated requirement in different documents.	Artificial Subjective
11.01.10.23.3	Space for plant and services should provide **adequate space** around the plant and services to permit inspection, maintenance and replacement. *Suggestion to improve sentence structuring:* 'adequate space' is an expression frequently used in the regulatory framework. It could be defined quantitatively and objectively by informing the actual needed space and dimensions in each situation, based on ergonomics	Artificial Subjective

6.3. The refined requirements taxonomy

Identifying these two different types of subjectivity consists of a further refinement to the proposed requirements taxonomy, presented in Sections 3 and 5.1. Both natural and artificial subjectivity can be used to classify subjective requirements, representing a further branch of the 'accuracy – subjective' elements. This addition originates an updated version of the requirements taxonomy (T2), shown in Fig. 7, highlighting the element 'logic rule'– 'yes' or 'no' as the final stage of the classification process, serving in practice as a trigger to automated compliance checking. In this process, requirements classified as 'yes' could lead to logic rules following the AS structure [59], while classes 1 to 4 [77] refer to the logical complexity associated to requirements data structure, as described in Section 3.

6.4. Recommendations for improving automated compliance checking

The recommendations were structured around two main topics, which represent improvement opportunities on the use of automated compliance checking in healthcare building design: (1) the need to revise statutory and guidance documents; and (2) strategies for designers to adopt automation in healthcare design compliance checking.

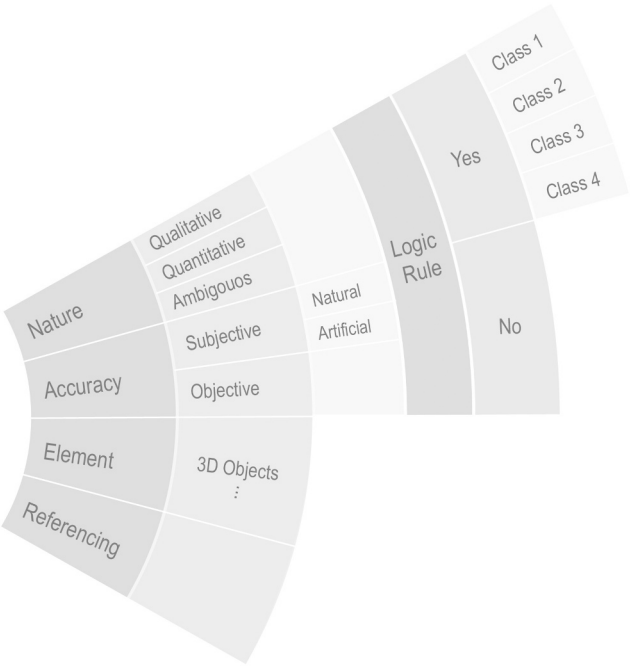

Fig. 7. Requirements taxonomy (T2).

6.4.1. Revision of healthcare design statutory and guidance documents

Regulations should be simplified by improving the structure of documents and making them better integrated. The large number of existing statutory and guidance documents, the repetition of information in different documents, and large incidence of cross-references between documents is disruptive as it increases the complexity of design development and assessment. It is challenging for designers to deal with so many requirements. The benefits of revising documents include (i) opportunity to update the content of requirements, considering the latest research evidence and specific issues e.g. Covid-19; (ii) an opportunity to eliminate duplication; and (iii) simplify and clarify the structure of the regulatory framework, helping designers to focus on the most important requirements for each project.

Improve consistency and clarity on language usage. One of the main issues while using information from statutory and guidance documents in automated compliance checking is vagueness and ambiguity arising from language usage. Hence, clearly defining the intended meaning e.g. of modal verbs such as 'must', 'should' and 'may' is an important step towards enabling a degree of automation. This would also help in reducing ambiguity and divergent interpretations by different stakeholders, and as such reduce rework, misunderstandings and derogations, supporting faster approval processes.

Clearly indicate requirements which could be easily used in automated checking systems. The taxonomy here proposed supports the identification of different types of regulatory requirements. This can be used to demonstrate to designers and those responsible for assessment which requirements could be easily automated, and which are subjective and as such might require detailed design consideration. One step towards enabling some level of future automation in practice is the clear indication in the documents of which requirements can be easily automated now. For this purpose, requirements could be visually indicated by a symbol in the main document or listed as an appendix. Diagrams, room layouts and floorplans could also indicate requirements that can be easily automated. From a practical perspective, designers and those responsible for design assessment can benefit from cost and time savings through this recommendation.

Reduce the amount of subjectivity in the regulatory and guidance documents. Subjective requirements cannot be simply eliminated from the documents because of the intrinsic subjective character of the design process. Natural subjective requirements should be used only when they are fundamental, so the creative aspect of design will not be constrained. Artificial subjectivity should be eliminated in such documents, ensuring better use of coherent, objective and quantifiable sentences in the revision of regulations. This could be achieved through the use of examples, graphical representation, better sentence writing and definition of more precise terms in the requirements.

6.4.2. Recommendations for designers (to support the implementation of some level of automated compliance)

Implement automated approaches wherever possible. Automation of specific tasks can help designers by (i) supporting better decision-making through improved information availability and (ii) providing time gains by eliminating the need for designers to do repetitive and elementary tasks. The application of these approaches can also aid design visualisation, supporting improved awareness and feedback from stakeholders. The use of automation should be supported by transparent and intuitive processes, so inconsistencies and eventual mistakes can be identified and promptly corrected.

Natural subjective requirements should be carefully considered in all stages of the design process, so value generation is supported. It is likely this type of requirements will continue to be part of regulatory and guidance documents, so appropriate approaches are needed to support their consideration in design e.g. semi-automated design support systems. The use of design support systems can have a greater impact on decision-making. They can aid designers on their creative process, while ensuring some degree of compliance through better information availability and guidance. Such systems would still be helpful for a standard room design approach, which by default should already be compliant. Design support systems could assist designers to assemble rooms and individual components into a functioning building, which involves natural subjective requirements and creative reasoning.

Designers can develop in-house rule databases and checking routines. The taxonomy here presented can help designers identify easily automatable requirements and develop in-house rule databases and routines to enable automated checking. They could use commercially available software like SMC, but also Visual Programming Language (VPL) tools such as Dynamo and Grasshopper, as plug-ins to modelling tools. This becomes especially relevant in situations where SMC rules are not flexible enough to represent the requirements logic structure. The main benefit for designers to incorporate these elements to their development process is to simplify compliance checking. They should be implemented throughout the design, rather than at end of stages, potentially reducing rework and time dedicated to resolve non-compliances later in the process.

Automated compliance checking systems should be structured according to design stages and to different Levels of Development (LOD). Design teams should assess design compliance during all stages of design development, according to its major stages (e.g. RIBA Plan of Work in the UK). This complements the previous recommendation, which indicates the need for designers to use a systematic approach to compliance checking. Further research is needed in relation to making information readily available to design teams over different design development stages.

6.5. Critical analysis of results

Healthcare regulatory documents have been developed in a piecemeal way over the years, with poor consideration of the complexity of overall regulatory framework. This process creates practical challenges for designers to ensure compliance, and also inhibit attempts to implement automation.

The analysis presented in Section 5.2 provides evidence of the challenge associated to the transition from manual to automated compliance approaches. The complexity associated with the current regulatory framework is noteworthy. Practitioners have evidenced through

interviews that the use of statutory and guidance documents in practice is diffused and fragmented, which corroborates previous research findings [31,51]. One of the key reasons for this is because of the convoluted sentence structure and plethora of information, as well as the high number of cross-referencing observed in the documents.

In the analysed documents, 3816 requirements were identified, with an average of 763 requirements per document. As the healthcare regulatory framework in the UK consists of at least 108 statutory and guidance documents, we estimate there are over 80 thousand requirements in the whole healthcare regulatory framework. The complexity arising from the number of requirements is further aggravated by the interdependency between different types of requirements and documents, making compliance checking difficult to be performed across the design process.

Most of the difficulties of using regulatory requirements in automated compliance checking reported by existing literature are linked to the fact automation has been approached mostly as a means to replace human operations. Interviews confirmed this is perceived in practice as a limiting perspective, and there is a need to address and explore how automation could be used more widely to support design decision making. Interviews, alongside with the dissemination activities and workshops from the final stage of the DSR, provided fundamental inputs to the proposition of recommendations. Most of the recommendations identify needed changes which rely on joint actions from multiple stakeholders.

From a methodological perspective, the recommendations presented in this paper are an output of DSR which could be understood as guidelines [29]. They were developed based on findings and insights from this research, focusing on overcoming major constraints identified in practice and reported by existing literature. Their development was based on outcomes from important sources of evidence, i.e. dissemination activities, semi-structured interviews, and implementation and refinement of a taxonomy (that was also originally developed following the DSR approach). Despite recommendations being developed within the UK healthcare building design domain, they could potentially be relevant and applicable to other contexts. From a DSR perspective, this suggests their instantiation could be further refined and evaluated in terms of their utility and applicability [17,48].

This paper has a particularly relevant methodological contribution, as it consists of an example of how and where typical DSR artefacts interact with each other. Furthermore, it demonstrates how activities undertaken following a DSR approach support developing and implementing specific artefacts, contributing to both theory and practice. This confirms two key aspects from DSR, evidenced by Hevner et al. [29] as: (i) outcomes of DSR being related to the artefact itself, but also to its associated construction and evaluation; and (ii) different types of artefacts being combined, so that innovation emerges through their implementation.

7. Conclusions

This research provided insights into the complexities of the UK healthcare regulatory framework, highlighting issues around the large number of regulatory and guidance documents and the high number of requirements. The use of DSR enabled an iterative research process in which artefacts were implemented, assessed in terms of utility, refined and developed based on multiple learning cycles.

The empirical study developed in this research demonstrated the importance of understanding information to be used in automated compliance checking. Results are based on the analysis of 5 documents from the UK only, and this is a limitation. Future research should extend the application of the taxonomy to a larger scale, analysing other relevant sets of documents such as the International Health Facility guidelines (iHFG).

The use of a taxonomy as described here is beneficial as it provides means to identify what types of information exist within existing statutory and guidance documents. It also includes the identification of subjectivity embedded in requirements, which was defined in this research as natural or artificial. Indeed, these two variants are based on the source of subjectivity in requirements, and future research on this topic is still needed due to its importance to the automated compliance checking subject. Additionally, the relationship between prescriptive or performance-based requirements to the proposed taxonomy has not been explored in this paper and should be addressed by further research.

This paper highlights strategies to support automated compliance checking for designers and those involved in the development of documents, through the proposition of recommendations. In practice, the taxonomy and the recommendations can improve the healthcare design process and can be used to create new documents or revise existing ones, even in different contexts from that reported in this paper. They also support eliminating unneeded subjectivity and identifying requirements that either can or cannot be automatically checked.

Results demonstrate that automation can be relatively easily achieved for quantitative and objective requirements, whereas subjectivity is still a fundamental constraint in the automated compliance process. Our research identified that while artificial subjective requirements could be simply eliminated, human knowledge still is needed to consider natural subjective requirements. This suggests that different types of automated compliance approaches are needed due to the diversity of requirements.

In this context of multiple approaches, hybrid solutions should be further explored as a means to deal with requirements subjectivity. They could potentially streamline the design process, reduce design rework and derogations, while improving compliance and supporting further applications of automation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] F.H. Abanda, J.H.M. Tah, R. Keivani, Trends in built environment Semantic Web applications: where are we today? Expert Syst. Appl. 40 (14) (2013) 5563–5577, https://doi.org/10.1016/j.eswa.2013.04.027. Elsevier Ltd.

[2] A. Akintoye, E. Chinyio, Private finance initiative in the healthcare sector: trends and risk assessment, Eng. Constr. Archit. Manag. 12 (6) (2005) 601–616, https://doi.org/10.1108/09699980510634155.

[3] I. Atoum, A. Otoom, Mining software quality from software reviews: research trends and open issues, Int. J. Comp. Trends Technol. 31 (2) (2016) 74–83, https://doi.org/10.14445/22312803/IJCTT-V31P114.

[4] V. Bazjanac, T. Maile, J. O'Donnell, Data environments and processing in semi-automated simulation with energyplus, Proc. CIB W78-W102 2011: Int. Conf. (2011) 26–28. http://itc.scix.net/data/works/att/w78-2011-Paper-93.pdf (March 5, 2019).

[5] 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, https://doi.org/10.1016/j.eswa.2015.02.029.

[6] M. Bhatt, J. Hois, O. Kutz, Ontological modelling of form and function for architectural design, Appl. Ontol. 7 (3) (2012) 233–267, https://doi.org/10.3233/AO-2012-0104.

[7] J. Braithwaite, R.L. Wears, E. Hollnagel, Resilient health care: turning patient safety on its head, Int. J. Qual. Health Care 27 (5) (2015) 418–420, https://doi.org/10.1093/intqhc/mzv063.

[8] M.C.B.F. Caixeta, A. Figueiredo, M.M. Fabricio, Desenvolvimento integrado de projeto, gerenciamento de obra e manutenção de edifícios hospitalares, Ambiente Construído 9 (2) (2009) 57–72. https://www.seer.ufrgs.br/ambienteconstruido/article/view/7420/5488 (accessed April, 2, 2021).

[9] J.R. Chellappa, BIM + Healthcare: Utilization of BIM in the Design of a Primary Healthcare Project, University of Hawai'i, 2009. http://hdl.handle.net/10125/45781 (accessed October, 25, 2016).

[10] J.R. Chellappa, H.H.-J. Park, BIM + healthcare: on the view of a primary healthcare renovation project, in: CAAD's New Frontiers: Proceedings of the 15th International Conference on Computer-Aided Architectural Design Research in Asia, 2010, pp. 293–302. http://papers.cumincad.org/data/works/att/caadria2010_028.content.00344.pdf (accessed October, 25, 2016).

[11] Department of Health and Social Care, Health Building Note 11–01: Facilities for Primary and Community Care Services. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/148509/HBN_11-01_Final.pdf, 2013.

[12] Department of Health and Social Care, Health Building Note 00–01. General Design Guidance for Healthcare Buildings. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/316247/HBN_00-01-2.pdf%0A, 2014.

[13] Department of Health and Social Care, Health Technical Memorandum 00. Policies and Principles of Healthcare Engineering. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/299276/HTM_00.pdf, 2014 (accessed Jun, 17, 2020).

[14] Department of Health and Social Care, The NHS Constitution for England. https://www.gov.uk/government/publications/the-nhs-constitution-for-england/the-nhs-constitution-for-england, 2015 (accessed May, 6, 2020).

[15] J. Dimyadi, R. Amor, Automated Building code compliance checking – Where is it at?, in: Proceedings of CIB WBC 2013, 2013, pp. 172–185, https://doi.org/10.13140/2.1.4920.4161.

[16] J. Dimyadi, P. Pauwels, R. Amor, Modelling and accessing regulatory knowledge for computer-assisted compliance audit, J. Inform. Technol. Constr. 21 (July) (2016) 317–336. http://www.itcon.org/2016/21 (accessed May, 27, 2017).

[17] A. Dresch, D.P. Lacerda, J.A.V. Antunes, Design Science Research: A Method for Science and Technology Advancement, Springer International Publishing, Cham, Switzerland, 2015, https://doi.org/10.1007/978-3-319-07374-3.

[18] C. Eastman, J. Lee, Y. Jeong, J. Lee, Automatic rule-based checking of building designs, Autom. Constr. 18 (8) (2009) 1011–1033, https://doi.org/10.1016/j.autcon.2009.07.002.

[19] E. Enache-Pommer, M.J. Horman, J.I. Messner, D. Riley, A unified process approach to healthcare project delivery: synergies between greening strategies, lean principles, and BIM, in: Construction Research Congress 2010, American Society of Civil Engineers, Reston, VA, 2010, pp. 1376–1405, https://doi.org/10.1061/41109(373)138.

[20] S.J. Fenves, J.H. Garrett, H. Kiliccote, K.H. Law, K.A. Reed, K.A. Reed, Computer representations of design standards and building codes: US perspective, Int. J. Constr. Inform. Technol. Univ. Salford UK 3 (1) (1995) 13–34. https://www.researchgate.net/profile/James-Garrett-5/publication/30869803_Computer_representations_of_design_standards_and_building_codes_US_perspective/links/54312cf20cf277d58e96dee8/Computer-representations-of-design-standards-and-building-codes-US-perspective.pdf (accessed May, 4, 2019).

[21] Fiatech, AutoCodes Project: Phase 1, Proof-of-Concept Final Report. http://www.fiatech.org/images/stories/techprojects/project_deliverables/Updated_project_deliverables/AutoCodesPOCFINALREPORT.pdf, 2012 (accessed December, 21, 2017).

[22] Fiatech, AutoCodes Phase II Report. http://www.fiatech.org/images/stories/projects/FiatechAutoCodesPh2-Report-Sept2015.pdf, 2015 (accessed December, 21, 2017).

[23] J. Fiksel, F. Hayes-Roth, Computer-aided requirements management, Concurr. Eng. 1 (2) (1993) 83–92, https://doi.org/10.1177/1063293X9300100201.

[24] C. Formoso, F. Leite, L. Miron, Client requirements management in social housing: a case study on the residential leasing program in Brazil, J. Constr. Dev. Countries 16 (2) (2011) 47–67. http://eprints.usm.my/42181/1/ART3_jcdc16-2.pdf (accessed April, 20, 2020).

[25] V. Fortineau, T. Paviot, S. Lamouri, Automated business rules and requirements to enrich product-centric information, Comput. Ind. 104 (2019) 22–33, https://doi.org/10.1016/j.compind.2018.10.001. Elsevier B.V.

[26] W. Gesler, M. Bell, S. Curtis, P. Hubbard, S. Francis, Therapy by design: evaluating the UK hospital building program, Health Place 10 (2) (2004) 117–128, https://doi.org/10.1016/S1353-8292(03)00052-2.

[27] P. Ghannad, Y.C. Lee, J. Dimyadi, W. Solihin, Automated BIM data validation integrating open-standard schema with visual programming language, Adv. Eng. Inform. 40 (January) (2019) 14–28, https://doi.org/10.1016/j.aei.2019.01.006.

[28] B. Hardin, D. McCool, BIM and Construction Management: Proven Tools, Methods, and Workflows, 2nd ed., John Wiley and Sons, Indianapolis, IN, 2015 (ISBN: 978-1-118-94277-2).

[29] Hevner, March, Park, Ram, Design science in information systems research, MIS Q. 28 (1) (2004) 75, https://doi.org/10.2307/25148625.

[30] C. Hicks, T. McGovern, G. Prior, I. Smith, Applying lean principles to the design of healthcare facilities, Int. J. Prod. Econ. 170 (2015) 677–686, https://doi.org/10.1016/j.ijpe.2015.05.029.

[31] S. Hignett, J. Lu, An investigation of the use of health building notes by UK healthcare building designers, Appl. Ergon. 40 (4) (2009) 608–616, https://doi.org/10.1016/j.apergo.2008.04.018. Elsevier Ltd.

[32] E. Hjelseth, Classification of BIM-based Model checking concepts, J. Inform. Technol. Constr. 21 (October) (2016) 354–370. http://www.itcon.org/2016/23 (accessed May, 22, 2017).

[33] J. Holmström, M. Ketokivi, A.-P. Hameri, Bridging practice and theory: a design science approach, Decis. Sci. 40 (1) (2009) 65–87, https://doi.org/10.1111/j.1540-5915.2008.00221.x.

[34] L. Jiang, R.M. Leicht, Supporting automated constructability checking for formwork construction: an ontology, J. Inform. Technol. Constr. 21 (October) (2016) 456–478. http://www.itcon.org/2016/28 (accessed May, 22, 2017).

[35] M. Kadolsky, K. Baumgärtel, R.J. Scherer, An ontology framework for rule-based inspection of eeBIM-systems, Proc. Eng. 85 (5) (2014) 293–301, https://doi.org/10.1016/j.proeng.2014.10.554.

[36] M. Kagioglou, R. Cooper, G. Aouad, M. Sexton, Rethinking construction: the generic design and construction process protocol, Eng. Constr. Archit. Manag. 7 (2) (2000) 141–153, https://doi.org/10.1108/eb021139.

[37] J.M. Kamara, C.J. Anumba, N.F.O. Evbuomwan, Establishing and processing client requirements: a key aspect of concurrent engineering in construction, Eng. Constr. Archit. Manag. 7 (1) (2000) 15–28, https://doi.org/10.1108/eb021129.

[38] E. Kasanen, K. Lukka, A. Siitonen, The constructive approach in management accounting research, J. Manag. Account. Res. 5 (1993) 243–264. https://mycourses.aalto.fi/pluginfile.php/183797/mod_resource/content/1/Kasanen%20et%20al%201993.pdf (accessed October, 26, 2016).

[39] H. Kim, J.-K. Lee, J. Shin, J. Choi, Visual language approach to representing KBimCode-based Korea building code sentences for automated rule checking, J. Comp. Design Eng. Soc. Comp. Design Eng. 6 (2) (2019) 143–148, https://doi.org/10.1016/j.jcde.2018.08.002.

[40] A. Kiviniemi, Requirements Management Interface to Building Product Models, Stanford University, 2005. https://www.researchgate.net/profile/Arto-Kiviniemi/publication/248399790_Requirements_management_interface_to_building_product_models/links/564f902f08ae1ef9296ead6b/Requirements-management-interface-to-building-product-models.pdf (accessed August, 22, 2017).

[41] B. Kollberg, J.J. Dahlgaard, P.P.-O. Brehmer, Measuring lean initiatives in health care services: issues and findings, Int. J. Product. Perform. Manag. 56 (1) (2006) 7–24, https://doi.org/10.1108/17410400710717064.

[42] M. Laakso, A. Kiviniemi, The IFC standard - a review of history, development, and standardization, Electron. J. Inf. Technol. Constr. 17 (May) (2012) 134–161. http://www.itcon.org/2012/9 (accessed April, 25, 2017).

[43] H. Lee, J.K. Lee, S. Park, I. Kim, Translating building legislation into a computer-executable format for evaluating building permit requirements, Autom. Constr. 71 (2016) 49–61, https://doi.org/10.1016/j.autcon.2016.04.008. Elsevier B.V.

[44] J.-K. Lee, C.M. Eastman, Y.C. Lee, Implementation of a BIM domain-specific language for the building environment rule and analysis, J. Intell. Robot. Syst. 79 (3–4) (2014) 507–522, https://doi.org/10.1007/s10846-014-0117-7.

[45] P.-C. Lee, T.-P. Lo, M.-Y. Tian, D. Long, An efficient design support system based on automatic rule checking and case-based reasoning, KSCE J. Civ. Eng. 23 (5) (2019) 1952–1962, https://doi.org/10.1007/s12205-019-1750-2.

[46] K. Lukka, The constructive research approach, in: L. Ojala, O.-P. Hilmola (Eds.), Case Study Research in Logistics, Publications of the Turku School of Economics and Business Administration, Series B1 (2003), 2003, pp. 83–101. https://www.researchgate.net/profile/Kari-Lukka/publication/247817908_The_Constructive_Research_Approach/links/5cf669fda6fdcc8475032f22/The-Constructive-Research-Approach.pdf (accessed May, 14, 2020).

[47] S. Macit İlal, H.M. Günaydın, Computer representation of building codes for automated compliance checking, Autom. Constr. 82 (June) (2017) 43–58, https://doi.org/10.1016/j.autcon.2017.06.018.

[48] S.T. March, G.F. Smith, Design and natural science research on information technology, Decis. Support. Syst. 15 (4) (1995) 251–266, https://doi.org/10.1016/0167-9236(94)00041-2.

[49] D. Marchant, The design brief: requirements and compliance, J. Inform. Technol. Constr. 21 (November) (2016) 337–353. http://www.itcon.org/2016/22 (accessed May, 22, 2017).

[50] E.A. Mendonça, L. Manzione, E. Hjelseth, Converting Brazilian accessibility standard for BIM-based code checking using RASE and SMC, in: 7th CIB W78 Information Technology for Construction Conference (CIB W78), Sao Paulo, 2020, pp. 291–307, https://doi.org/10.46421/2706-6568.37.2020.paper021.

[51] G.R.W. Mills, M. Phiri, J. Erskine, A.D.F. Price, Rethinking healthcare building design quality: an evidence-based strategy, Build. Res. Inf. 43 (4) (2015) 499–515, https://doi.org/10.1080/09613218.2015.1033880. Taylor & Francis.

[52] N. Nawari, The challenge of computerizing building codes in a BIM environment, Comp. Civil Eng. 1 (2012) 285–292, https://doi.org/10.1061/9780784412343.0036.

[53] N.O. Nawari, Intelligent design codes, in: Structures 2009: Don't Mess with Structural Engineers, 2009, https://doi.org/10.1061/41031(341)251.

[54] N.O. Nawari, Automating codes conformance, J. Archit. Eng. 18 (December) (2012) 1–30, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000049.

[55] N.O. Nawari, BIM-model checking in building design, Struct. Congr. 2012 (2012) 941–952, https://doi.org/10.1061/9780784412367.084.

[56] N.O. Nawari, SmartCodes and BIM, in: Structures Congress 2013, 2013, pp. 928–937, https://doi.org/10.1061/9780784412848.082.

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

[58] J. Nicholas, An integrated lean-methods approach to hospital facilities redesign, Hosp. Top. 90 (2) (2012) 47–55, https://doi.org/10.1080/00185868.2012.679911.

[59] S. Park, Y.C. Lee, J.K. Lee, Definition of a domain-specific language for Korean building act sentences as an explicit computable form, J. Inform. Technol. Constr. 21 (September) (2016) 422–433. http://www.itcon.org/2016/26 (accessed May, 22, 2017).

[60] P. Parsanezhad, V. Tarandi, R. Lund, Formalized requirements management in the briefing and design phase, a pivotal review of literature, J. Inform. Technol. Constr.

21 (May) (2016) 272–291. http://www.itcon.org/2016/18 (accessed May, 26, 2017).
[61] D. Passman, Planning healthcare environments, in: M. Kagioglou, P. Tzortzopoulos (Eds.), Improving Healthcare through Built Environment Infrastructure, Wiley-Blackwell, Salford, UK, 2010 (ISBN: 978-1-405-15865-7).
[62] P. Pauwels, D. Van Deursen, R. Verstraeten, J. De Roo, R. De Meyer, R. Van De Walle, J. Van Campenhout, A semantic rule checking environment for building performance checking, Autom. Constr. 20 (5) (2011) 506–518, https://doi.org/10.1016/j.autcon.2010.11.017. Elsevier B.V.
[63] P. Pauwels, T.M. de Farias, C. Zhang, A. Roxin, J. Beetz, J. De Roo, C. Nicolle, A performance benchmark over semantic rule checking approaches in construction industry, Adv. Eng. Inform. 33 (2017) 68–88, https://doi.org/10.1016/j.aei.2017.05.001. Elsevier Ltd.
[64] P. Pauwels, S. Zhang, Semantic rule-checking for regulation compliance checking: an overview of strategies and approaches, in: Proceedings of the 32nd CIB W78 Conference 2009, 2015, pp. 619–628. https://biblio.ugent.be/publication/6890589 (accessed July, 21, 2017).
[65] P. Pauwels, S. Zhang, Y.C. Lee, Semantic web technologies in AEC industry: a literature overview, Autom. Constr. 73 (2017) 145–165, https://doi.org/10.1016/j.autcon.2016.10.003. Elsevier B.V.
[66] S.L. Pfleeger, N. Fenton, S. Page, Evaluating software engineering standards, Computer 27 (9) (1994) 71–79, https://doi.org/10.1109/2.312041.
[67] E. Pikas, L. Koskela, S. Sapountzis, B. Dave, R. Owen, Overview of building information modelling in healthcare projects, in: HaCIRIC International Conference, Manchester, UK, UK, 2011, pp. 286–298. http://eprints.hud.ac.uk/25915 (accessed April, 20, 2020).
[68] C. Preidel, A. Borrmann, Automated code compliance checking based on a visual language and building information modeling, in: Proceedings of the 32nd International Symposium of Automation and Robotics in Construction, 15–18 June, 2015, pp. 256–263, https://doi.org/10.13140/RG.2.1.1542.2805.
[69] C. Preidel, A. Borrmann, Towards code compliance checking on the basis of a visual programming language, J. Inform. Technol. Constr. 21 (July) (2016) 402–421. http://www.itcon.org/2016/25 (accessed May, 22, 2017).
[70] A. Rankin, J. Lundberg, R. Woltjer, C. Rollenhagen, E. Hollnagel, Resilience in everyday operations: a framework for analyzing adaptations in high-risk work, J. Cogn. Eng. Decision Making 8 (1) (2014) 78–97, https://doi.org/10.1177/1555343413498753.
[71] A.W. Righi, T.A. Saurin, Complex socio-technical systems: characterization and management guidelines, Appl. Ergon. 50 (2015) 19–30, https://doi.org/10.1016/j.apergo.2015.02.003. Elsevier Ltd.
[72] K. Schwabe, J. Teizer, M. König, Applying rule-based model-checking to construction site layout planning tasks, Autom. Constr. 97 (November 2017) (2019) 205–219, https://doi.org/10.1016/j.autcon.2018.10.012. Elsevier.
[73] C.B. Seaman, Qualitative methods in empirical studies of software engineering, IEEE Trans. Softw. Eng. 25 (4) (1999) 557–572, https://doi.org/10.1109/32.799955.
[74] R. Sengonzi, P. Demian, S. Emmitt, Optimising healthcare facility value through better briefing and optioneering, in: Proceedings of the 9th International Postgraduate Research Conference (IPGRC), Research Institute for the Built and Human Environment (BuHu), Salford, UK, 29–30 January 2009, 2009, pp. 352–365. https://repository.lboro.ac.uk/articles/conference_contribution/Optimizing_healthcare_facility_value_through_better_briefing_and_optioneering/9433220 (accessed June, 01, 2018).
[75] W. Solihin, J. Dimyadi, Y.-C. Lee, C. Eastman, R. Amor, Simplified schema queries for supporting BIM-based rule-checking applications, Autom. Constr. 117 (May) (2020) 103248, https://doi.org/10.1016/j.autcon.2020.103248. Elsevier.
[76] W. Solihin, J. Dimyadi, Y. Lee, In search of open and practical language-driven BIM-based automated rule checking systems, in: I. Mutis, T. Hartmann (Eds.), Advances in Informatics and Computing in Civil and Construction Engineering, Springer International Publishing, Cham, 2019, pp. 577–584, https://doi.org/10.1007/978-3-030-00220-6_69.
[77] W. Solihin, C. Eastman, Classification of rules for automated BIM rule checking development, Autom. Constr. (2015), https://doi.org/10.1016/j.autcon.2015.03.003.
[78] W. Solihin, C.M. Eastman, A knowledge representation approach in BIM rule requirement analysis using the conceptual graph, J. Inform. Technol. Constr. 21 (March) (2016) 370–401. http://www.itcon.org/2016/24 (accessed May, 05, 2017).
[79] J. Soliman-Junior, C.T. Formoso, P. Tzortzopoulos, A semantic-based framework for automated rule checking in healthcare construction projects, Can. J. Civ. Eng. 47 (2) (2020) 202–214, https://doi.org/10.1139/cjce-2018-0460.
[80] J. Soliman Junior, J.P. Baldauf, C.T. Formoso, P. Tzortzopoulos, Using BIM and lean for modelling requirements in the design of healthcare projects, in: 26th Annual Conference of the International Group for Lean Construction, Chennai, 2018, pp. 571–581, https://doi.org/10.24928/2018/0455.
[81] J. Soliman Junior, J.P. Baldauf, P. Tzortzopoulos, C.T. Formoso, M. Kagioglou, The role of building information modelling on assessing healthcare design, in: CIB World Building Congress 2019: Constructing Smart Cities, International Council for Research and Innovation in Building and Construction, Hong Kong, 2019, pp. 1659–1672, in: https://site.cibworld.nl/dl/publications/WBC19/WBC_Proceedings_June2019_Complete.pdf (accessed May, 20, 2021).
[82] I. Sommerville, Software Engineering, Addison-Wesley Publishing Company, Wokingham, England, 2007 (ISBN: 978-7-111-19770-6).
[83] X. Tan, A. Hammad, P. Fazio, Automated code compliance checking for building envelope design, J. Comput. Civ. Eng. 24 (2) (2010) 203–211, https://doi.org/10.1061/(ASCE)0887-3801(2010)24:2(203).
[84] P. Tzortzopoulos, P. Chan, R. Cooper, Requirements management in the design of primary healthcare facilities, in: Proceedings of the Simposio Brasilierio de Gestao e Economia de Construcao, 2005. http://www.research.lancs.ac.uk/portal/en/publications/requirements-management-in-the-design-of-primary-healthcare-facilities(07805b77-3590-45c7-962d-3109020e36a2)/export.html (accessed May, 20, 2021).
[85] Q.Z. Yang, Y. Zhang, Semantic interoperability in building design: methods and tools, CAD Comp. Aided Design 38 (10) (2006) 1099–1112, https://doi.org/10.1016/j.cad.2006.06.003.
[86] A. Yurchyshyna, C. Faron-Zucker, N. Le Thanh, A. Zarli, Adaptation of the domain ontology for different user profiles: application to conformity checking in construction, Lect. Notes Busin. Inform. Proc. 45 (LNBIP) (2010) 128–141, https://doi.org/10.1007/978-3-642-12436-5_10.
[87] A. Yurchyshyna, A. Zarli, An ontology-based approach for formalisation and semantic organisation of conformance requirements in construction, Autom. Constr. 18 (8) (2009) 1084–1098, https://doi.org/10.1016/j.autcon.2009.07.008. Elsevier B.V.
[88] J. Zhang, N.M. El-Gohary, Automated information transformation for automated regulatory compliance checking in construction, J. Comput. Civ. Eng. 29 (4) (2015), https://doi.org/10.1061/(asce)cp.1943-5487.0000427.
[89] J. Zhang, N.M. El-Gohary, Semantic-based logic representation and reasoning for automated regulatory compliance checking, J. Comput. Civ. Eng. 31 (1) (2017), 04016037, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000583.
[90] 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, https://doi.org/10.1016/j.autcon.2012.06.006.