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ARTICLE

A semantic-based framework for automated rule checking in healthcare construction projects[1]

Joao Soliman-Junior, Carlos T. Formoso, and Patricia Tzortzopoulos

Abstract: Healthcare projects are known for having a high degree of complexity. Furthermore, the design of healthcare facilities is highly constrained by regulations containing a wide range of requirements. Using BIM for automated rule checking has been pointed out as an opportunity to improve requirements management in these projects. However, most existing research is focused on hard-coded approaches or on limited sets of requirements. The aim of this investigation is to propose a semantic-based framework for automated rule checking in the context of healthcare design. An empirical study was conducted in the redevelopment of a university hospital, using Design Science Research as a methodological approach. Results indicate that the nature of regulations and the subjectivity of requirements have a major impact on the possibility of their translation into logical rules, which is needed to enable automated checking. The main theoretical contribution is a taxonomy for automated rule checking and information transformation.

Key words: semantics, healthcare design, Building Information Modelling (BIM), automated rule checking, requirements management.

Résumé : Les projets de soins de santé sont réputés pour leur degré élevé de complexité. En outre, la conception d'installations de soins de santé est fortement limitée par des réglementations renfermant un vaste éventail d'exigences. Le recours à la modélisation des données du bâtiment (MDB) pour la vérification automatisée des règles a été souligné comme un moyen d'améliorer la gestion des exigences dans ces projets. Toutefois, la plupart des recherches existantes sont axées sur des approches préprogrammées ou sur des ensembles limités d'exigences. L'objectif de cette étude est de proposer un cadre sémantique pour la vérification automatisée des règles dans le contexte de la conception des installations de soins de santé. Une étude empirique a été menée dans le cadre du réaménagement d'un hôpital universitaire, en utilisant la recherche en science de la conception (« Design Science Research ») comme approche méthodologique. Les résultats indiquent que la nature des réglementations et la subjectivité des exigences ont un impact majeur sur la possibilité de les traduire en règles logiques, ce qui est nécessaire pour permettre une vérification automatisée. La principale contribution théorique est une taxonomie pour la vérification automatisée des règles et la transformation de l'information. [Traduit par la Rédaction]

Mots-clés : sémantique, conception des soins de santé, modélisation des données du bâtiment (MDB), vérification automatisée des règles, gestion des exigences.

1. Introduction

Requirements management has long been described as one alternative to improve the performance of construction projects in terms of value generation (Kamara et al. 2000; Parsanezhad et al. 2016). Requirements management consists of systematic steps for capturing requirements, processing information, and making it available to design teams, as well as controlling whether requirements from different stakeholders are properly considered in design solutions (Kamara et al. 2000). Recent literature indicates that Building Information Modelling (BIM) can be used to support requirements management, by storing semantic information and enabling automated rule checking of design solutions (Kiviniemi 2005; Eastman et al. 2009; Jallow et al. 2014; Parsanezhad et al. 2016; Fortineau et al. 2019).

Healthcare projects are known for having a high degree of complexity in design, construction, and operations (Enache-Pommer et al. 2010). The complexity of healthcare facilities results from the fact that there is a large number of subsystems and a wide diversity of requirements involved (Tzortzopoulos et al. 2005). There is also uncertainty as healthcare processes evolve rapidly, which demands frequent changes in the built environment (Tzortzopoulos et al. 2005). Moreover, the design of healthcare buildings is highly constrained by existing sets of regulations, which usually contain a large amount of prescriptive information. During design reviews, design specifications must be checked against existing regulations to achieve conformance to legal requirements. Hence, detailed checking of building design in relation to regulations and applicable standards is a key part of the design process (Nawari 2013; Kim et al. 2019; Lee et al. 2019; Ghannad et al. 2019; Schwabe et al. 2019).

Despite being an important task, compliance checking is often carried out manually. This is time consuming and may result in

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arbitrary interpretations of requirements, partly due to ambiguities and inconsistencies in regulations, leading to negative design iterations, long lead time, and design mistakes (Eastman et al. 2009; Bhatt et al. 2012; Zhong et al. 2012; Nawari 2013; Hardin and McCool 2015; Zhang and El-Gohary 2015, 2017; Preidel and Borrmann 2015, 2016; Jiang and Leicht 2016; Lee et al. 2016; Macit İlal and Günaydın 2017). Moreover, manual compliance checking tends to be inconsistent because it relies on human judgment and interpretation, which are ambiguous due to previous personal experiences and biases, and unwritten local understandings of the regulations are implicitly considered (Fiatech 2012; Solihin and Eastman 2015). Therefore, using BIM for automated rule checking has been pointed as one of the main opportunities for improving requirements management in complex projects (Fortineau et al. 2019) such as healthcare buildings.

In recent years, BIM-based commercial computer tools have been developed, and data exchanges have become more complex as technology has advanced (Laakso and Kiviniemi 2012). Some research studies have explored the development of automated rule checking, mainly by developing new computational languages (Lee et al. 2015; Zhang and El-Gohary 2015; Preidel and Borrmann 2015, 2016; Park et al. 2016; Solihin and Eastman 2016) and new approaches for rule analysis and compliance (Nawari 2009; Yurchyshyna and Zarli 2009; Yurchyshyna et al. 2010; Pauwels et al. 2011, 2017*a*, 2017*b*; Kadolsky et al. 2014; Beach et al. 2015; Pauwels and Zhang 2015; Dimyadi et al. 2016; Hjelseth 2016; Jiang and Leicht 2016; Zhang and El-Gohary 2017).

Moreover, some studies (Yang and Zhang 2006; Yurchyshyna et al. 2010; Pauwels et al. 2011, 2017*a*, 2017*b*; Zhong et al. 2012; Torma 2013; Kadolsky et al. 2014; Beach et al. 2015; Pauwels and Zhang 2015; Zhang and El-Gohary 2017) suggest that semantics must play a key role in advances associated to automated rule checking. These studies have established an important link between the functionalities of semantic technologies and rule extraction, representation, interpretation, and execution.

However, most of these advancements are focused on hard-coded approaches (i.e., related to programming languages and computational systems) or appear to be limited when the context of application is different from the one that they were specifically developed for, resulting from specific sets of requirements (e.g., structural analysis of reinforced concrete systems). Therefore, further research into holistic perspectives that enable a broader application of automated rule checking is needed. There is a need to explore how semantic information could be transformed in the conversion of regulations into logical rules for automation to enable a broader adoption of automated rule checking of healthcare design.

The aim of this paper is to propose a semantic-based framework for automated rule checking in the context of healthcare construction projects. This framework was devised to support the development of automated regulatory rule checking systems considering the needs of end users, who generally use existing commercially available software for requirements modelling purposes. Moreover, the framework is intended to be helpful for regulatory agencies, organisations, and policy makers in need of developing and updating sets of regulations and for developers of BIM-based software tools. Additionally, this paper contributes towards the categorisation of regulatory information regarding sets of building codes and regulations for healthcare projects, i.e., the definition of a taxonomy, which helps to understand, structure, categorise, store, and retrieve information from regulatory requirements.

2. Building codes, regulations, and semantics

The involvement of different stakeholders in healthcare design and the identification and capture of their requirements are very important for a successful design output (Sengonzi et al. 2009; Nicholas 2012). This involves requirements related to product functions, attributes, and other characteristics (Kamara et al. 2002) originating from a diverse range of users' needs. In healthcare projects, requirements management needs to deal with the needs and expectations of different stakeholders that may have conflicting interests (Kamara et al. 1999), including patients, visitors, medical staff, administrative staff, and people in charge of maintenance and operation of the facilities (Kollberg et al. 2006; Sengonzi et al. 2009). Therefore, requirements management plays an important role by making available different sets of data related to stakeholders' needs and expectations. Furthermore, requirements must be seen not just as measurable properties, but also as data containing semantic-rich information, which is not always explicit and properly understood for decision making in the design process (Solihin and Eastman 2015).

Traditionally, sets of building codes and regulations are written, applied, and read by people (Eastman et al. 2009). This process, based on natural language, includes a large number of complex expressions, which can lead to ambiguity, contradictions, and vagueness while translating sentences into a computer-executable format (Eastman et al. 2009; Lee et al. 2016; Ghannad et al. 2019). To be effective, building code models (i.e., set of rules written under a computer-executable language) must be (Macit İlal and Günaydın 2017): (*i*) comprehensive enough to deal with the complex nature of codes and regulations; (*ii*) capable of representing all types of information; (*iii*) flexible to be maintained and controlled by different users (i.e., nonprogrammers should be able to add or modify rules inside the system); (*iv*) linked to building code documents and other sets of regulations to simplify the consistency checking process; and (*v*) be developed considering the overall set of regulations, instead of focusing on individual rule representations, by creating means to prevent contradictions among rules. Besides, a rule written under a computable form should encode the requirements logic within itself (Marchant 2016), reflecting relationships between the logical elements of a sentence.

Although it is usually clear which information from requirements should be represented in rules when using a computer-executable language, existing initiatives for encoding building regulations into computer-executable formats still require manual efforts (Zhang and El-Gohary 2015; Kim et al. 2019; Lee et al. 2019; Schwabe et al. 2019). Thus, the process of translating human-readable and natural language into a computable format requires a "logical reliable rule-making process" (Lee et al. 2016, p. 53), which must be based on the core information (i.e., the fundamental parts of a phrase) that defines the meaning of the sentence.

This is defined as semantics, or "meanings of terminologies" (Chen and Vernadat 2003, p. 277). Zhang and El-Gohary (2015, p. 3) further state that semantics "aims at capturing the meanings of a domain or topic […] in a structured manner". Floridi (2005, p. 367) enhances this definition by formalising the concept of semantic information as "well-formed, meaningful, and truthful data" that should be understood in terms of content about a subject. Therefore, based on these conceptualisations, efforts in translating sets of building codes and regulations into a computer-executable format must focus on the processed, structured, and meaningful data (Chen and Vernadat 2003; Floridi 2005; Zhang and El-Gohary 2015), hereby defined as semantic information.

The development of computer-interpretable models for automated rule checking is mostly based on parametric object modelling and parametric rule modelling (Lee et al. 2015). There is a wide range of rules that can be parameterised (Solihin and Eastman 2015). When a set of rules is narrowed down to regulatory checking, additional challenges may emerge, related to the sources of information that serve as input for rule modelling, which sometimes might be open for interpretation, making information modelling difficult to be performed (Macit İlal and Günaydın 2017). That is why the process of identifying the nature of regulations and the associated information hierarchy is a core task in the development of successful automated models for rule checking (Macit İlal and Günaydın 2017).

3. Recent research on automated rule checking

A major research initiative on automated rule checking was led by FIATECH, named AutoCodes Project. That project began in 2011 (Phase 1) with the aim of validating the use of automated technology for real-world code compliance assessment and the acceleration of the regulatory approval process (Fiatech 2012). Phase 1 investigated the transformation of the regulatory code review process. During that phase, inconsistencies between different jurisdictions such as contradictory requirements were identified and documented. At the end of AutoCodes Phase 2 (Fiatech 2015), which started in 2013, the project successfully demonstrated the feasibility of adopting automated compliance methods for building design and achieved a better understanding of the automated rule checking processes.

Solihin and Eastman (2015) proposed four classes of parametric rules for the purpose of automated rule checking: (*i*) Class 1, rules that require a single or a small amount of explicit data; (*ii*) Class 2, rules that require simple derived attribute values; (*iii*) Class 3, rules that require extended data structure; and (*iv*) Class 4, rules that require a "proof of solution". Basically, these classes are related to the logical complexity associated to data structures in both the geometric model and rule sentences; thus, Class 1 is the least complex, and Class 4 presents the highest degree of complexity.

Different approaches for automated rule checking have been proposed. Zhang and El-Gohary (2015) devised the information transformation method (ITr) algorithm, based on the semantic natural language processing (NLP) approach. This algorithm intends to transform instances from a set of regulations of a specific building code into quantitative requirements through logic clauses. This transformation approach appears to be a promising way of shaping information according to specific needs such as those observed in an automated rule checking environment. However, those authors expect variability in performance due to the diverse textual aspects across different sets of building codes and regulatory documents.

Zhang and El-Gohary (2017) have later developed a schema for representing and reasoning about regulatory requirements focused in automated rule checking of building designs. This schema is based on the First Order Logic (FOL) approach and has provided important contributions to the development of this research. This is because those authors have formalised a new way of representing regulatory information, based on a logical structure, aligned with the use of a semantic and ontological approach.

Preidel and Borrmann (2015, 2016) suggested that most of the existing approaches for automated rule checking fails because the regulatory information is too complex to be clearly represented by rules created by nonprogrammers. Those authors have proposed the Visual Code Checking Language (VCCL), a flow-based and visual programming language. They also pointed out that it is necessary to develop more elements capable of representing information by using VCCL because of the variety of codes and different ways of presenting information. Park et al. (2016) explored the KBimCode Language, a domain-specific language that aims to represent the regulatory sentences from the Korean building code under a standardised and easy to use syntax. It is based on the atomic sentence (AS) concept, which is a "declarative sentence that is either true or false and cannot be broken down into other simpler sentences" (Lee et al. 2016, p. 58). That means atomic sentences are the minimum unit for rule checking (Park et al. 2016), being composed by the SVO (subject–verb–object) structure. The AS approach provides a structured way for making fundamental elements of a sentence explicit during information transformations.

Dimyadi et al. (2016) presented an overview of several approaches to model and access regulatory knowledge. The need for an open standard regulatory knowledge representation was identified, which could create a favourable environment for efficient access to regulatory information. Kadolsky et al. (2014) proposed an ontology approach to support the semantic adoption of integrated models for energy performance analysis. Those authors demonstrated the feasibility of using an ontology-based description to support the definition of logical rules to verify models before performing energy analysis. Yurchyshyna et al. (2010) devised a method to adapt domain ontologies to different user profiles and contexts by using semantic principles. That study highlighted the need for acquiring and representing information in a consistent way, making it possible to check information in detailed queries, based on a semantic search tool.

Pauwels et al. (2017a) compared three rule checking approaches for semantic rule checking, pointing out key factors in the performance of this process, which include indexing algorithms, query rewriting techniques, and rule handling strategies. Beach et al. (2015) also explored the semantic approach for regulatory compliance, indicating that it allows one to specify and update regulations without the need of significant software development. Therefore, a need for change in the way regulations are written was identified, as human readable documentation should be seen as an output of the codes, instead of an input to rule creation (Beach et al. 2015).

In summary, previous research identified that there is much diversity in regulations and that the transformation of information into computer readable rules for automated rule checking remains a challenge. Some studies have focused on the development of algorithms and computational languages, whereas others have proposed alternative approaches to deal with the challenges of this subject. It seems that previous research studies are mostly related to the development of different solutions, system prototypes, and methods for automated rule checking. The achievements described through the literature review such as the development of the KBimCode Language (Park et al. 2016), the information transformation (Zhang and El-Gohary 2015), and the schema for representing and reasoning about regulatory requirements (Zhang and El-Gohary 2017), based on a logical structure aligned with the use of semantic and ontology principles, provide fundamental conceptualisations and developments that strongly support the development of the semantic-based framework proposed in this article.

Understanding and analysing requirements is a fundamental step towards automated rule checking of building models (Solihin and Eastman 2016). This is because the lack of understanding of which sets of information should be collected and analysed represents a critical issue (Heaton et al. 2019). It is assumed that a semantic approach, based on the meaning of elements, can help to analyse how the consistency of logic rules is affected by the sources of data from sets of building codes and other regulatory documents. Additionally, a semantic approach may provide effective means for transforming information along design reviews.

4. Research method

Design Science Research (DSR) was the methodological approach adopted in this investigation. DSR has a prescriptive character and can be used both to create innovative solution concepts to solve classes of problems faced in the real world, named artefacts, and to contribute to the development of mid-range theories, i.e., theoretical models that are applicable to a limited range of situations (Kasanen et al. 1993; Lukka 2003). In contrast to traditional descriptive research, in which theories need to be validated, the artefact must be assessed against the criteria of value or utility (March and Smith 1995). DSR has been used in several fields of knowledge, including information systems, operations man-

Table 1. Interviews of Phase 1.

Number	Date	Source of evidence	Approximate duration	Interviewee profile	Understanding: Research problem	Understanding: Specific context
01	5 December 2016	Open interview	45 min	Director of the Emergency Unit		×
02	5 December 2016	Open interview	1 h 30 min	Director of the Emergency Unit		×
03	24 May 2017	Open interview	45 min	Site engineer	×	×
04	24 May 2017	Open interview	2 h 15 min	Architect responsible for the design coordination	×	×
05	6 July 2017	Open interview	2 h 10 min	Architect responsible for the legal design	×	×
06	12 July 2017	Open interview	1 h 15 min	On-site engineer responsible for MEP checking		×
07	27 July 2017	Open interview	1 h	Site engineer	×	×
08	18 August 2017	Open interview	50 min	On-site engineer responsible for MEP checking	×	×
09	3 October 2017	Open interview	70 min	Architect responsible for regulatory compliance		×
10	20 December 2017	Open interview	40 min	Architect who participated in the latest revision of RDC 50	×	×

agement, and, more recently, in the context of design, production and operations of the built environment (Voordijk 2009). In this research study, the proposed artefact is a semantic-based framework that supports the modelling of regulatory requirements for automated rule checking in the design of healthcare projects.

An empirical study was conducted in close collaboration with a university hospital (Hospital A). This hospital is located in Porto Alegre, Brazil, and the existing facilities were under a major process of redevelopment, with the construction of two new buildings. The total new built-up area corresponds to approximately 84 000 m^2, increasing the existing operational area by 70%. Within Hospital A, this study was limited to the Emergency Unit. This unit is to be installed on the ground floor of the new building and was chosen because of the complexity related to the design of this particular type of built environment, related to the multiple and flexible use of spaces and diversity of clinical and patient flows. This redevelopment project was chosen for different reasons: (*i*) both medical and engineering staff of Hospital A were willing to collaborate in this research study, due to the need to improve the quality of the built environment; (*ii*) this project was considered to be a very complex design due to the size and particular characteristics of this hospital; and (*iii*) several process improvements have been implemented in this hospital based on operations management concepts and principles, which have created new demands for the built environment. The research process was divided into three phases, which correspond to the main phases of DSR, as suggested by Holmström et al. (2009), namely understanding the problem, development of the artefact, and analysis and reflection.

At the beginning of this investigation, most of the design had already been completed — detail design of furniture, definition of equipment, and wayfinding devices were still being developed, and the construction phase had started. Thus, the first stage consisted of understanding the context of this healthcare project, especially how the design compliance process was undertaken. The main sources of evidence were the following: (*i*) 10 open-ended interviews (with architects and engineers from the Department of Construction and Maintenance of the Hospital A and other stakeholders such as the director of the Emergency Unit and people in charge of the latest revision of RDC 50); (*ii*) 3 direct observations performed in the context of Hospital A (existing emergency unit and in the building construction site, regarding MEP installation and checking); (*iii*) analysis of design documents and different types of regulatory documents and analysis of requests for design changes from the hospital staff to the design team; and (*iv*) analysis of design assessment reports, performed by the design team and regulatory agencies. Those sources of evidence were useful for understanding how information had been originated and transformed during design and how that had impacted on the process of checking regulatory requirements. These also helped understanding where the design team members searched for information to support decision-making during design. Table 1 is related to the source of evidence for *i*, in which detailed information regarding the profile interviewees is provided, as well as how each of these interviews have supported understanding either the research problem or the specific context of Hospital A, in both existing facilities and in the redevelopment project.

In Phase 2, the content involved in the checking process was mapped through classification of healthcare building design regulations and process information related to requirements from regulations with the aim of making them explicit. The proposed framework emerged during the research process, based on insights obtained from the process of mapping regulations and exploring both traditional and automated rule checking methods.

There are several sets of regulations and standards that affect healthcare design within the Brazilian context such as the local building and fire codes, accessibility, and building performance standards. However, one of the limitations of this investigation is that it is based on only one set of regulations, named Resolution RDC number 50, established in 2002 by the Brazilian National Agency for Health Surveillance (Agência Nacional de Vigilância Sanitária 2002). This is the most important set of regulations for the design of healthcare facilities in Brazil. RDC 50 requirements were classified according to four criteria, which were established according to not only the literature, but also the information elicited in the empirical study.

In Phase 3, the framework was assessed according to criteria of utility and applicability, as suggested by March and Smith (1995). This evaluation was mostly based on 11 open-ended interviews and also on insights obtained during the process of transforming the content of regulations into rules. The framework and the evaluation criteria were presented to the interviewees, and they were asked to talk about their understanding of the content of the framework. The profile of the interviewees and their specific contributions are presented on Table 2, according to the framework's different stages of development.

5. Results

5.1. Phase 1

Design reviews were performed manually in the redevelopment project of Hospital A. Some information for checking compliance against regulations were stored in a spreadsheet: if there were inconsistencies between design elements and regulations, these were marked individually. According to one of the design team members, this process was very time consuming and difficult to carry out, due to the complexity of the building and the large amount of information involved. In this project, a preliminary internal design checking process was carried out before the coordination of the designs from different disciplines started.

Table 2. Interviews of Phase 3.

Number	Date	Stage of framework	Approximate duration	Interviewee profile	Scope of the evaluation
01	19 October 2017	Version 1	65 min	Researcher and PhD candidate with experience in the design for health and BIM	General evaluation of the artefact, comprehension of the connections, taxonomies and layout modifications
02	10 January 2018	Version 2	45 min	Professor, knowledge on IFC and BuildingSMART International member	General evaluation, emphasis on the information transformation
03	12 January 2018	Version 2	30 min	Professor, knowledge on BIM	General evaluation and suggestion of new approaches
04	20 January 2018	Version 2	40 min	Director of software for IFC properties management	General evaluation, emphasis on the technological development for the suggested approach
05	12 February 2018	Version 3	45 min	Professor, knowledge on healthcare design	General evaluation of the artefact
06	13 February 2018	Version 3	25 min	PhD candidate, knowledge on design collaboration	General evaluation of the artefact
07	13 February 2018	Version 3	30 min	PhD candidate, knowledge on Lean Construction	General evaluation of the artefact
08	13 February 2018	Version 3	20 min	Professor, knowledge on Lean Construction and design theory	General evaluation of the artefact and layout suggestions
09	21 March 2018	Version 4	55 min	Professor, knowledge on healthcare design and BIM	General evaluation of the artefact and connections with the overall design process
10	26 March 2018	Version 4	55 min	Director of automated rule checking software developing company	General evaluation of the artefact, emphasis on the application and validation of empirical data
11	28 March 2018	Version 4	25 min	Professor, knowledge on design for health and wellbeing	General evaluation of the artefact and of the categorisation process

Table 3. Categories for classifying requirements.

Classification number	Classification name	Criteria
1	Nature	Qualitative, quantitative, or ambiguous (if it is not possible to identify the predominance of qualitative or quantitative information)
2	Possibility of translation into logical rule	The sentence in the requirement can be rewritten in a logic way, i.e., it is possible to define both content and condition elements — this classification is binary, it either can or cannot be translated
3	IFC object in the 3D model related to the requirement	The relationship between requirements and the associated geometry in the 3D model, based on the IFC classification format
4	Class of parametric rule	Requirements able to be translated into logical rules according to classes 1–4 (Solihin and Eastman 2015)

The process of assessing design compliance against the regulations of the Brazilian Health Surveillance Agency was carried out over a long period, as any instance of noncompliance would prevent the use and operation of the building but not prevent its construction. However, this caused much design rework during the construction phase.

5.2. Phase 2

5.2.1. Classification of resolution RDC 50

Four criteria were used to classify RDC 50 requirements, considering the content and the origin of requirements: (*i*) nature; (*ii*) possibility of translation into logical rules; (*iii*) relationship of the requirements to IFC objects in the 3D model; and (*iv*) classes of parametric rules, as defined by Solihin and Eastman (2015). These categories are explained in Table 3.

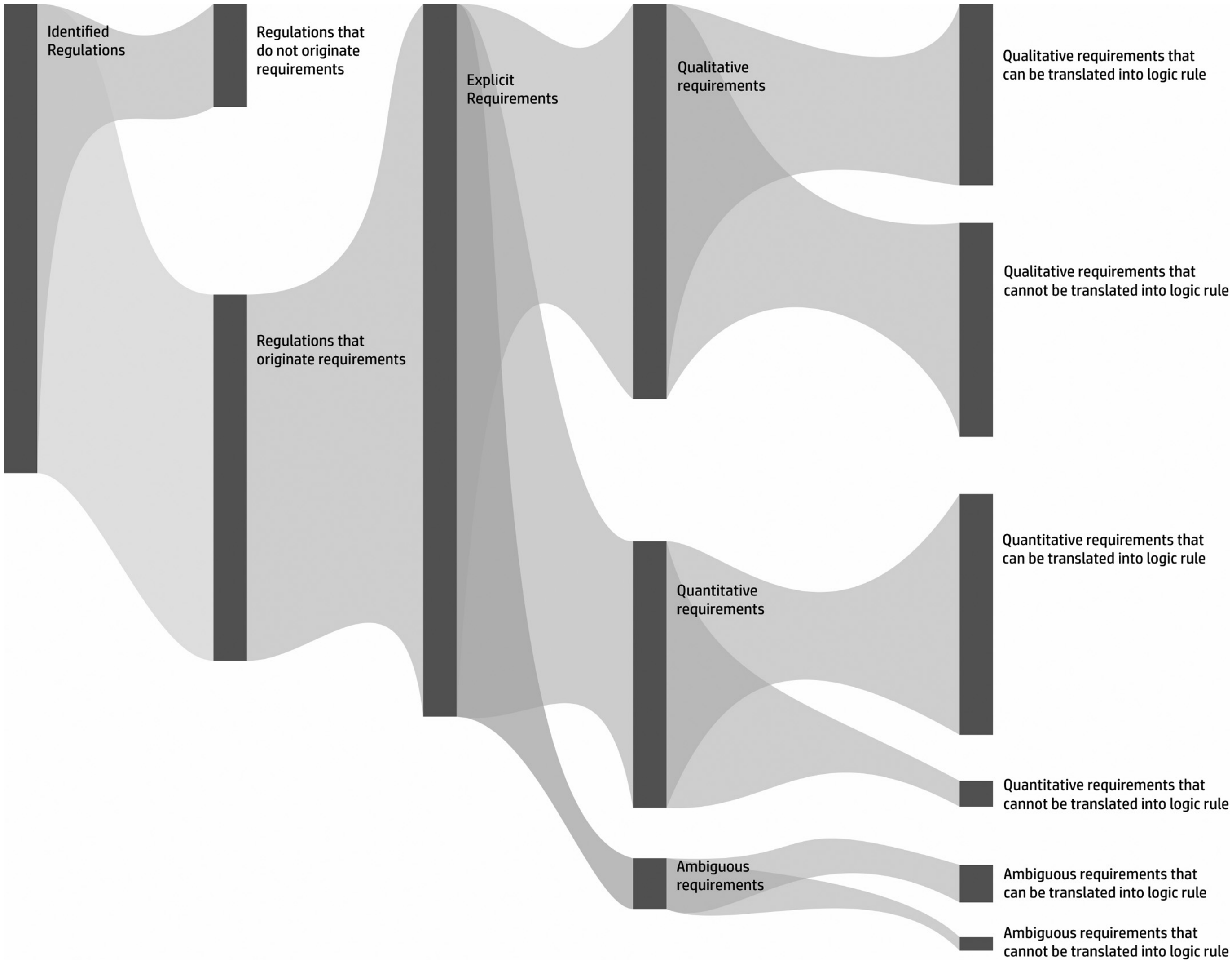
RDC 50 has 820 regulations, from which 1284 requirements were identified. In fact, many RDC 50 regulations contain more than one requirement, and some requirements that are included in the content of a single regulation often belong to different categories and hierarchical levels. Thus, each single requirement captured in this study is related to an individual product attribute. The quantitative results obtained for each classification criteria are as follows:

(*i*) Nature. 56% of requirements were classified as qualitative, 37% as quantitative, and 7% as ambiguous.

(*ii*) Possibility of translation into logic rule. 63% of requirements can be translated into logical rules (i.e., re-written in a logical way). This classification does not consider any specific commercial software, and it is simply based on the analysis of the possibility of restructuring the requirements into a logical sentence, which include terms associated to content and condition.

(*iii*) Relationship of the requirement to IFC objects in the 3D model. From the requirements able to be translated into logical rules, 371 standalone occurrences of IFC Space were identified. It means that those requirements can be verified by checking properties and parameters only from the IFC Space object. Additionally, 349 occurrences of IFC Space combined with other IFC types were observed. Those types of requirements could be verified by

Fig. 1. Relationship among RDC 50 classifications.



checking the existence of another IFC type object inside the IFC space object.

(*iv*) Class of parametric rule. From the requirements able to be translated into logical rules, 70% fit into class 1, 28% fit into class 2, and the remaining 2% are classified as class 3 or 4.

Figure 1 presents the relationships between the RDC 50 regulations and requirements. The vertical bars indicate the proportion of occurrences, and from the left to the right, these unfold into the proposed categories. It shows that the majority of requirements are qualitative, and a large share of quantitative requirements can be translated into logic rules.

Figure 2 compares the nature of requirements and the possibility to translate them into logical rules. It indicates that almost 90% of quantitative requirements and 54% of qualitative requirements could be translated into logic rules. Despite the difference in the percentage, the total number of qualitative requirements able to be represented in a logic structure is relevant (314). Regarding ambiguous requirements, most of them can be translated into logical rules, similarly to quantitative requirements. Examples of different types of requirements and their classification are provided in Table 4.

Figure 3 presents a matrix that classifies each requirement according to the specialty that they belong to, based on the original structure and content of RDC 50. This structure is divided into eight healthcare functionalities (1–8) and five design criteria (A–E): (1) elective healthcare assistance and primary healthcare, (2) urgent and emergency healthcare assistance, (3) healthcare assistance for hospitalization, (4) healthcare support to diagnostics and therapy, (5) healthcare technical support, (6) healthcare development of human resources and research, (7) healthcare management and administrative support, and (8) healthcare logistics support; (A) internal and external circulation, (B) built environment comfort criteria, (C) built environment infection criteria, (D) common and special installations, and (E) fire safety criteria.

Based on the analysis of the matrix, it can be assumed that a large amount of requirements are related to the functionalities number 4 (healthcare support to diagnostics and therapy), and number 8 (healthcare logistics support), and design criteria related to Common and Special Installations. The functionality number 6 (healthcare development of human resources and research) and design criteria related to B (built environment comfort) are the ones with the smallest amount of information. This matrix helped us understanding which aspects of healthcare services concentrate more regulatory requirements, by visualising the overall content of the regulations, based on the classification process and taxonomies proposed by this investigation.

Fig. 2. Relationship among nature and possibility of translation to logical rule.

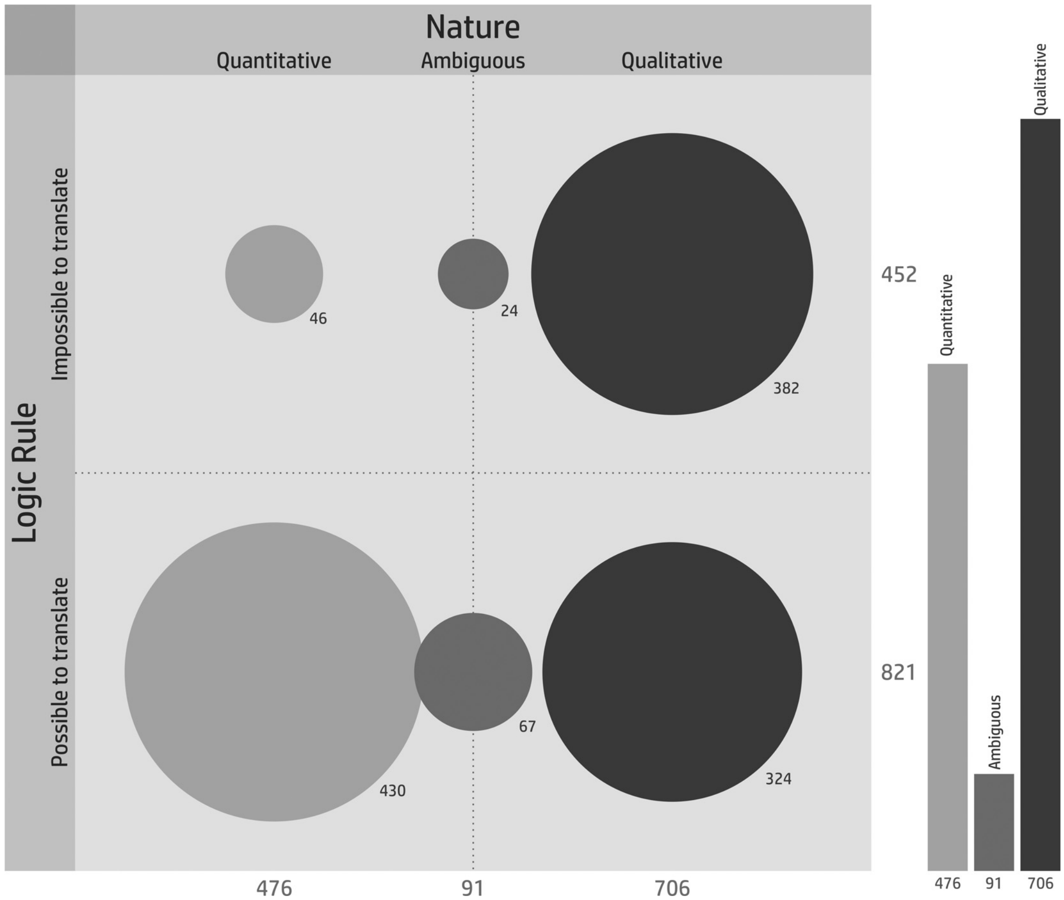


Fig. 3. Matrix classifying RDC 50 requirements according to the proposed taxonomies.

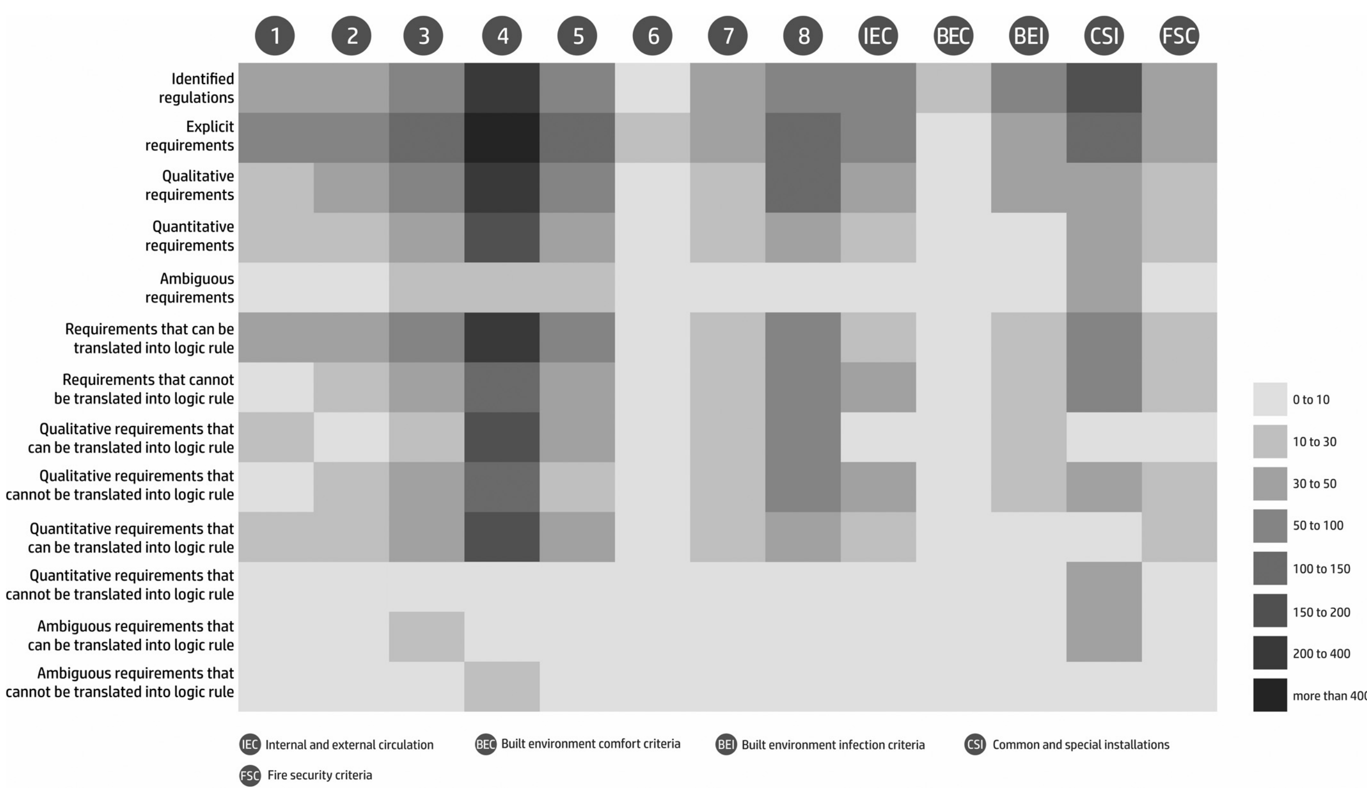


Table 4. Examples of requirement classifications from RDC 50.

Requirement	Nature	Possibility of translating into logic rule
The amount of beds in the physiotherapy diagnostics and therapy rooms depends on the activities developed within these spaces, as well as the individual patient demands.	Qualitative	No
The bed area in the physiotherapy diagnostics and therapy rooms must be equal or superior to 2.4 m^2.	Quantitative	Yes
In the intensive care unit, there should exist at least five individual and fully equipped beds, arranged in common, individual rooms, or both, depending on the healthcare unit's individual needs.	Ambiguous	No
The number of available stretchers should be equal to the number of operating theatres plus one. In this case, there should be considered only operating theatres in which low-complexity procedures are performed.	Ambiguous	Yes

6. Framework for automated rule checking of healthcare design projects

Figure 4 presents the framework which represents how information can be shaped for the automated checking of regulatory requirements, considering a holistic and nonfragmented perspective. It defines a set of structured tasks to support the verification of regulatory requirements during the design process. The framework is structured as follows: phases, internal processing, taxonomic elements, and interaction between phases and internal processing. Each of the elements of the framework is discussed below.

6.1. Phases

The framework relies upon understanding how regulatory information is processed and transformed during design. Thus, information is originated from regulatory sets of documents and regulations (Phase A — regulatory requirements); then, making it visible and available for data collection and storing (Phase B — explicit requirements); and finally, data can be clustered and analysed in a logical way (Phase C — codified requirements).

The data input must be the same if compared with the output, differing only on format and language. That is why all three phases are based on the requirement terminology (i.e., regulatory, explicit, and codified requirements), which means that the requirements are the same at the different phases, being, however, expressed and shaped in different ways, according to the needs of each phase.

6.2. Internal processing

The analysis of data processing at a detail level makes it possible to understand how semantic information is transformed. Two translation processes make this flow possible, representing data batch transfer between phases. The first translation process occurs between the regulatory requirement and the explicit requirement phases (TP1), and the second translation process happens from explicit requirements to the codified requirement (TP2). These data processing stages are presented in the framework based on the language which information is observed in each one of them and the relationship between information transformation and the translation process itself.

6.2.1. Translation process 1 (TP1)

The translation of information from regulatory requirements into explicit requirements consists mainly of classification activities. The act of classifying requirements results in the definition of a requirement hierarchy such as the one proposed by Kiviniemi (2005), which contributes to make requirements visible, storable, categorised, and organised. The language observed in this phase is human-machine readable, which enables both computational algorithms and people to interpret regulatory data.

6.2.2. Translation process 2 (TP2)

The translation of explicit requirements into codified requirements consists of codification activities, i.e., converting human-readable information into computational-readable data. On the internal processing perspective, data interpretation can be done by machines. When requirements are presented under a codified format, it is expected that they can be visualized as logical rules, which can be further used for the automated checking purposes. In each of the codified requirements, it is possible to observe both conditions and content elements, which are fundamental for creating logical expressions.

6.3. Taxonomic elements

Apart from the phases and the translation processes, there are some taxonomic elements related to the main structure of the framework. These elements help understanding some of the most important classifications for each phase, their associated components, and how they relate to each other. Each of these elements is discussed below.

6.3.1. Semantic information

Semantic information refers to processed, structured and meaningful data. It is the output of Phase A, which should be the result of extracting fundamental information from regulations. This process relies upon two main attributes: design and nature. Design represents the format in which regulations are displayed to the user and how this decision may affect the understanding of their content (e.g., graphs, text elements, tables, schemas, design examples, and sketches). Nature refers to how information is implicitly defined. In this framework, it is assumed that nature can be qualitative, quantitative, or ambiguous. Determining the nature of information can help understanding how regulations are created, and it is related to the processes of translating it into a logical rule.

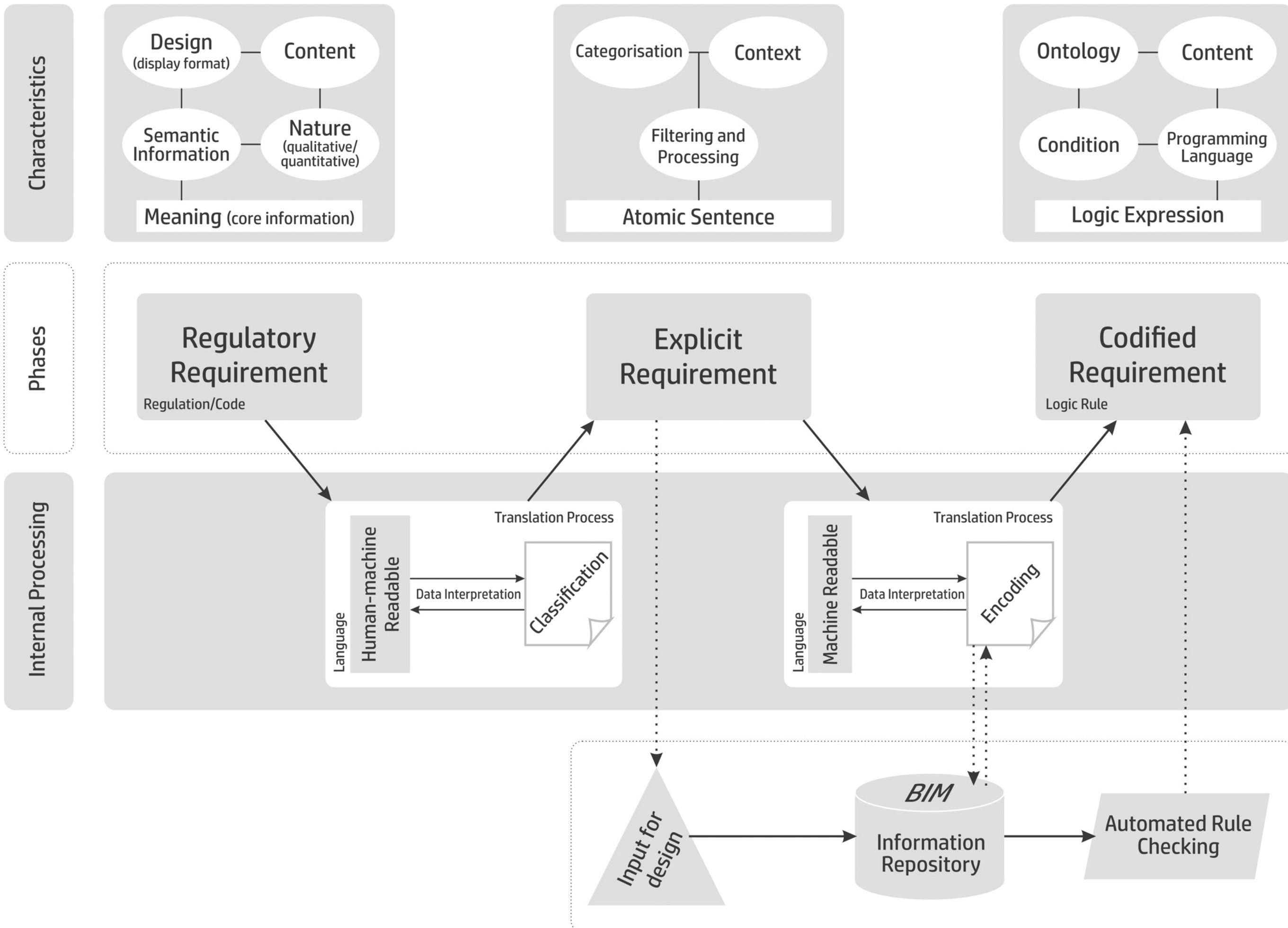
6.3.2. Atomic sentence

In this framework, an atomic sentence is the building block of logical expressions (Phase C), which are the content and condition structures. As this construct defines the output for Phase B, there are important characteristics that must be considered, namely requirements categorization and context. Requirements categorization is the process of categorisation is concerned with classifying requirements according to taxonomic categories based on a pre-defined hierarchical structure. Then, each regulation is defined considering a specific context. Such an understanding is important as it allows the correct interpretation of regulations, leading to consistent explicit requirements, i.e., requirements can be identified, stored, and used according to their specific context.

6.3.3. Logical expression

Logical expressions are the output of Phase C. Those expressions should be based on atomic sentences and correspond to the functional codified requirements. For structuring those expres-

Fig. 4. Framework for supporting the regulatory automated checking.



sions, there are characteristics that must be considered, namely content and condition. Content is the a part of the formalized sentence that is related to its meaning. Usually, this part of the sentence is composed by the subject and object (from the AS structure) (Park et al. 2016) such as object information, properties, and locations. Next, associated to the content, the condition part is usually related to the verb (from the AS structure) (Park et al. 2016), defining which criteria the content should satisfy. Altogether, content and condition form the basic logic expression.

6.4. Interaction between phases and internal processing

There is an interaction between the main phases and the internal processing, represented by a fourth module in the framework. This makes explicit some of the relationships of the framework with major elements of design and compliance in healthcare projects. First, explicit requirements should serve as an input for decision-making at the design phase. When design is developed using BIM, this enables the creation of a computational information repository. Then, data stored in a digital building model can be linked to encoding processes if converging ontologies and classifications are sustained. This fourth module suggests that the process of automated rule checking relies on codified requirements and their matching ontology with the 3D model and the checking interfaces.

6.5. Theoretical contributions

Table 5 presents the main constructs used for describing the framework, their original definitions, and the new conceptualizations proposed for the automated rule checking context. The main theoretical contributions of this research relate to the relationships between new conceptualisations, taxonomic elements, and the associated information transformation processes. The definition of three main constructs, represented by the main phases of the framework, enabled other important constructs to emerge. Some of the constructs used in this investigation are new conceptualisations such as the codified requirement and translation process.

Taxonomic elements are related to the classifications that were proposed during the development of the framework. Therefore, some of the framework elements are not taxonomies on their own right, but the sentences related to them could be clustered under a predetermined taxonomy, i.e., by determining the AS. Table 6 presents an overview of the framework elements and their relationships, which is another contribution of this research work.

6.6. Evaluation of the framework

The framework was assessed according to a set of utility and applicability criteria, as suggested by March and Smith (1995). The evaluation of the utility of the model, according to the proposed criteria, is presented as follows:

(a) Use of geometric and semantic information

The information transformation processes are the means to make information explicit. Some interviewees identified that aspects specifically related to requirements management steps could be better incorporated, i.e., by formalising the require-

Table 5. Constructs of the framework: adaptations and new conceptualizations.

Construct	Existing conceptualisation	New conceptualization for the automated rule checking context
Regulatory requirement	Regulations and laws are related to building design, production, planning, health, and safety. Other legal requirements are related to acquisition, operation, and demolition of the building (Kamara et al. 2000).	Regulatory requirements represent the origin of semantic information within the automated rule checking context.
Explicit requirement	Requirements are related to product functions, attributes, and other characteristics that are required by clients (Kamara et al. 2000), being concrete or abstract (Gutman 1982).	Explicit requirements are related to concrete or abstract data, visible for storing, organisation, and usage for design attributes.
Codified requirement	—	Codified requirements represent semantic information structured in a logical way for the codification and rule-making reasoning.
Translation processes	—	Translation processes transform and shape semantic information by classification or codification.
Semantic information	Semantic information aims at "capturing the meanings of a domain or specific topic […] under a structured manner" (Zhang and El-Gohary 2015). "[…] well-formed, meaningful and truthful data" (Floridi 2005).	Semantic information consists of processed, structured, and meaningful data.
Atomic sentence	"A declarative sentence that is either true or false and cannot be broken down into other simpler sentences" (Lee et al. 2016). That means atomic sentences are the minimum unit of rule checking (Park et al. 2016) and are composed by the SVO (subject–verb–object) structure.	Atomic sentence is the shortest way to express a sentence without losing semantic information.

Table 6. Relationship among the elements of the framework, separated by the modules of the framework (phases, internal processing, and taxonomic elements).

Elements of the framework	Key connections among the elements
Phases	
Regulatory requirement	The source of semantic information, which is defined based on the design and nature of regulations
Explicit requirement	A result from the TP1 of the regulatory requirements
Codified requirement	A result from the TP2 of the explicit requirements
Internal processing	
Translation process 1 (TP1)	TP1 transforms and shapes semantic information, by classification processes
Translation process 2 (TP2)	TP2 transforms and shapes semantic information by codification processes
Taxonomic elements	
Design	The display format of regulations, associated to the understanding of the regulatory requirements
Nature	To understand how semantic information is taxonomically incorporated into the regulation and is related to TP1 and TP2
Semantic information	The processed, structured, and meaningful data
Context	Understanding the context of each regulation allows incorporating the semantic information to explicit requirements in a consistent way
Requirements categorisation	Explicit requirements must be classified into categories and hierarchical structures
Atomic sentence	Obtained from the semantic information and can be used to form a logic expression
Content	The part of the atomic sentence related to its meaning
Condition	The criteria that the content of the atomic sentence should meet for the compliance reasoning
Logic expression	Originated from atomic sentences and is formed by the content and condition elements, which can be used for creating codified requirements

ments' hierarchical structures. Additionally, geometric and semantic information becomes critical, as these must be explicit, consistent, and properly classified and stored. Thus, the correct use of standards such as IFCs is fundamental to a rule checking process.

(b) Consistency of the modelling and checking processes

Interviewees identified that by using the framework, data tend to become more consistent, if compared with traditional approaches. This criterion was not fully evaluated because the framework was not implemented in practice.

(c) Precision of automated checking

This is related to the consistency of information. Interviewees suggested that as the framework provided a systematic and structured approach, it is expected that checking processes should be less ambiguous and prone to error.

(d) Scope of use

Interviewees pointed out that the framework should be functional for different types of use. However, the framework was not fully evaluated according this criterion, as it was not fully tested in practice.

(e) Information traceability

As the framework involves explicit requirements through systematic processes, interviewees pointed out that it will provide formalised data, which can be traced.

The applicability of the framework was evaluated through the following criteria:

(a) Easiness of use for different users

The framework was well understood by the majority of the interviewees. Although this is positive, a full evaluation of the framework easiness of use should be based on a practical implementation, which has not happened.

(b) Translation of regulations into logical rules

Interviewees mentioned that translation processes also occur during traditional approaches but not in a formalised and structured way, as proposed by the framework.

(c) Information transparency

Interviewees suggested that transparency should be increased by using the framework because it involves a continuous effort of dealing with semantic information.

Thus, it is believed that regulatory agencies, organisations, and policy makers can benefit from the use the framework, as it should support the processes of developing new sets of regulations, as well as updating existing ones. Such institutions may benefit from the fact they could write sets of regulations knowing that these could be easily verified automatically. Additionally, programmers and software developers can use the framework to support the development of new BIM-based tools focusing on automated rule checking. These could benefit from the understanding of how semantic information is transformed, in the development of new software solutions. Therefore, they could also provide new tools to support the use and application of the framework by end users such as architects and engineers during the design process.

7. Conclusions

This research work has proposed a framework for understanding the activities and taxonomies involved in automated regulatory review process, pointing out how a well-established flow of information is fundamental for successful design outputs in healthcare construction projects.

The process of classifying regulations under the four categories defined in this research helped defining taxonomic elements and understanding important characteristics of healthcare regulatory requirements. Furthermore, it supported the understanding of how information originated from sets of regulations impact the possibility of a successful translation into logical rules. Mapping regulations in the semantic flow of information approach also appear to be a promising way to support requirements management. This is because it promotes a better understanding of aspects such as the nature and content of requirements, helping to explicit requirements and store them as an organised database. Thus, the framework presented in this paper helps to promote a structured and systematic way of shaping regulatory information for the purpose of automated rule checking.

The main outcomes of this research work, as suggested by March and Smith (1995) for design science approach, are summarized in Table 7.

The understanding of taxonomies is important, as it has a direct impact on the application of automated rule checking. This is because they enable understanding important characteristics of information that will be used as an input for the purpose of rule creation. Furthermore, the analysis carried out after the classification process helped to demonstrate that the typology of information relates directly to the possibility of translation of the regulatory requirements into logical rules.

Table 7. Outcomes of design science research.

Outputs of the design science (March and Smith 1995)	Framework
Solution (conceptual model)	Framework for support the automated checking of regulatory requirements
Constructs	Conceptual elements used for describing the framework and their relationships (Table 5)
Method	(1) Sequence of steps that represent the main phases of the framework; (2) fourth module of the framework, related to the application of automated rule checking

The results from the classification process used in this research indicate that a high percentage of qualitative requirements could be translated into logical rules by the proposed semantic approach. Therefore, the way in which sets of regulations are written may compromise the overall development of automated rule checking systems, as there is a need to change the way in which this process is conceived and carried out. However, results from this study indicate that translating requirements into logical rules for the purpose of automated rule checking relies on the nature of regulations, how the content of regulations is structured, and (c) which degree of subjectivity is embedded in the regulation definition process. Therefore, the relationship between nature, structure of content, and subjectivity could either enable an automated rule checking system or hamper its practical development and adoption.

Additionally, the relationship between automated rule checking systems with BIM is explored in this framework. It is assumed that it can serve as an information repository and database for geometry, properties, and rules, as a common ontology background can be created.

Even though a fully-automated scenario is desirable, the findings of this study indicate that currently not all requirements for healthcare construction projects can be fully translated in terms of automated rule processing and checking. Although this decreases the overall degree of automation in the design process, semi-automated processes may provide benefits to the healthcare context. Some regulatory requirements rely mostly on subjectivity, which depends on human interpretation and creativity, to be fully considered in healthcare design. Therefore, automated rule checking developments should be focused on the repetitive and less value-adding activities, whereas human problem-solving capacities could be better used for highly subjective checking or for performing creative and more value-adding tasks during healthcare design by using semi-automated approaches.

Finally, this research highlights the importance of the semantic information approach (and its associated flow, transformations, meanings, and structures) in design, especially on complex environments such as the one usually observed in healthcare construction projects.

A major limitation of this investigation is that the artefact proposed in this research work is at the level of solution incubation. Indeed, the framework was developed during the empirical study carried out in a single healthcare project, not being tested in other projects or contexts to this date.

Regarding further research, this framework needs to be refined and tested with other sets of regulations. The framework needs to be fully implemented in practice and could potentially be tested in the future with other types of buildings. As a consequence, the proposed framework might evolve, and thus, new relationships may emerge, considering its existing elements or the introduction of new elements. This would also contribute towards extending the framework for automated rule checking to an even broader scope and more holistic perspective.

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