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Developing an Ontology for Concrete Surface Defects to Enhance Inspection, Diagnosis and Repair Information Modeling

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Abstract: Facility maintenance requires thorough inspections throughout a facility's lifecycle to ensure structural integrity and longevity. A significant challenge lies in managing the semantic relationships between various inspection data across different lifecycle phases and effectively representing inspection results. While numerous studies have focused on identifying, analyzing, repairing, and preventing defects, organizing and integrating this information systematically for future use remains unaddressed. This paper introduces the Ontology for Concrete Surface Defects (OCSD), a unified knowledge model that enables stakeholders to access information systematically. OCSD aims to enhance future asset management systems by providing comprehensive knowledge about concrete surface defects, encompassing inspection, diagnosis, 3R (Repair, Rehabilitation, and Replacement), and defect concepts. Although the integration with Building Information Modeling (BIM) standards like the Industry Foundation Classes (IFC) is not undertaken in this study, OCSD provides a foundational framework that can facilitate such mappings in subsequent studies or applications. The methodology includes reviewing existing literature to define relevant concepts, outlining steps for developing OCSD, creating its basic components, and evaluating its effectiveness. The semantic representation of OCSD was assessed through a survey, confirming its ability to clarify concepts and relationships in this field.

Keywords: ontology; concrete surface defects; defect modeling; inspection; diagnosis; repair; BIM

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1. Introduction

The quality of buildings and infrastructure systems depends heavily on regular inspections to detect defects that exceed tolerance levels, necessitating timely repairs. Maintaining these systems in good condition throughout their lifecycle requires rigorous inspection and maintenance processes. Recent studies on Building Information Modeling (BIM) have demonstrated significant potential for extending BIM applications to the construction, operation, and maintenance phases of facilities. BIM models evolve during different lifecycle phases to reflect changes related to quality inspection and repair processes. In this context, an ontology, which is a knowledge model that helps clarify and systematize implicit knowledge, can play a critical role in making this information logically accessible to users [1]. Ontologies can create unified knowledge models to facilitate information exchange within the construction industry and standardize processes and frameworks for using BIM in facilities management.

The effective management of defects is critical for ensuring the safety and performance of infrastructure systems, especially aging structures such as bridges. Recent studies highlight the growing necessity for integrating defect assessments into broader frameworks like risk assessment and prioritization to address challenges in large-scale infrastructure management [2,3]. Moreover, detailed knowledge of defects plays a crucial role in assessing the structural integrity and residual capacity of structures. For instance, Pinho et al. [4] emphasized that accurate defect data are essential for forensic analyses aimed at understanding the root causes of failures.

However, the considerable amount of data resulting from inspections poses significant management challenges. Efficiently handling these data is crucial to avoid errors, reduce costs, and optimize resource utilization. Critical issues include establishing semantic relationships between various inspection data across lifecycle phases and effectively representing inspection results [5]. Although numerous studies have focused on identifying, analyzing, repairing, and preventing defects, there remains a gap in organizing and integrating this information systematically for future use. Specifically, there is a need for a comprehensive ontology to streamline research efforts, reduce duplication, and provide a high-level approach to modeling knowledge related to the inspection, diagnosis, and repair of concrete surface defects.

To address these challenges, the objective of this paper is to develop an ontology that covers the different types of information and concepts related to the inspection, diagnosis, and the Repair, Rehabilitation, and Replacement (3R) of concrete surface defects. This ontology, called OCSD (Ontology for Concrete Surface Defects), extends our previous work [6] and focuses on concrete surface defects regardless of the type of structure. For instance, in infrastructure projects such as bridges, OCSD enables stakeholders to systematically model and manage information related to common defects like cracks, spalling, and delamination caused by environmental factors and load stresses. This enhances the efficiency of the inspection process and informs diagnosis and repair strategies. Designed to be applicable at various lifecycle phases, including construction and operation and maintenance (O&M), OCSD provides a unified framework for efficient data management, stakeholder collaboration, and the integration of new data collection technologies. While mapping OCSD to BIM schemas like Industry Foundation Classes (IFC) is outside this paper's scope, it establishes a foundation for future integrations. By serving as a basis for IFC mapping, OCSD can enhance BIM-based systems with detailed knowledge of concrete surface defects, improving interoperability and data exchange in the construction industry. Additionally, previous studies highlight how defect risk assessments could complement OCSD frameworks to prioritize maintenance strategies in infrastructure systems [2,3].

The paper is structured as follows: the subsequent section reviews the relevant literature, followed by an in-depth discussion of OCSD development. The next section examines the evaluation of OCSD, and the final section outlines the key findings and future research directions.

2. Literature Review

2.1. Concrete Infrastructure Management

Regular inspection and appropriate Repair, Rehabilitation, and Replacement (3R) works are crucial for the continued operations of infrastructure systems [7–11].

2.1.1. Types of Defects

Gheitasi and Harris [12] evaluated the effect of subsurface delamination of the reinforced concrete deck. Deterioration of concrete elements often occurs in steel bars as corrosion and section loss due to leakage from expansion joints adjacent to supports. Cracks in concrete are caused by dead and live loads, stresses due to temperature changes, and shrinkage. Each of these cracks can provide a space for the penetration of chloride, moisture, or salt, resulting in the formation of new defects.

Nielsen et al. [13] presented a framework to gather concrete bridge defects data, investigate defect severity, and recommend a prioritized repair portfolio for critical components. Le and Andrews [14] classified the various components of the bridge according to the component type and material, and defined the extent of repair actions (e.g., repair or replacement) and related condition states based on the severity and extent of the defects. Brandon et al. [15] asserted that bridge failure can be the result of issues in one of the following processes: design, construction, operation, or inspection.

Defects caused by one damage mechanism can accelerate the formation of other defects, leading to further damage. Therefore, the relationship between defects and the condition of the defective element requires further study. For example, acid reactions damage the protective layer, exposing the underlying layer to the environment, which can lead to chloride penetration and corrosion. The aging process of concrete materials and various aggressive agents are among the factors that cause damage over time [16].

The most common types of surface defects in concrete based on the Concrete Structures Protection, Repair and Rehabilitation book [17] and Ontario Structure Inspection Manual (OSIM) [18] are: (1) cracks, (2) spalling, (3) delamination, (4) scaling, (5) disintegration, (6) erosion, (7) honeycombing, (8) pop-outs, (9) cold joints, (10) stratification, (11) segregation, (12) efflorescence, (13) exudation, (14) incrustation, (15) stalactites, (16) abrasion/wear, (17) slippery surfaces, and (18) stains. Table 1 shows the types of concrete defects based on OSIM. Crack defects are partial or complete linear fractures on the concrete surface. An oriented crack usually has a particular slope and direction. A mapped crack occurs randomly at close distances without a fixed direction and often covers a large area [19,20]. Spalling involves a significant gap caused by the local separation of concrete from a larger surface. Delamination is the lack of bonding of a portion of the separated concrete surface that is not entirely detached from the larger surface. Scaling is the loss of part of the mortar or concrete surface in the form of surface peeling. Disintegration is the breaking of concrete into smaller sections or parts, which usually occurs if severe scaling is not controlled over time. Erosion is mechanical damage and loss of mass caused by scrubbing sand and other particles in running water on the concrete surface. Honeycombing refers to voids between the coarse particles of concrete. A pop-out is a cone-shaped hole on the surface. Cold joints are interconnected linear separations at the joints between pouring two sets of concrete. Segregation results from the separation of cement and different sizes of aggregates. Stratification is separation in the form of a layered and horizontal structure due to high humidity and vibration. Efflorescence is characterized by white salt deposition on the surface [21]. Exudation involves the release of a substance from a compound, which in concrete is the release of gel-like material from surface pores [22]. Incrustation is the appearance of crusts or the accumulation of hard coating on the surface [23]. Stalactites are accumulations of substances hanging from the surface due to chemical reactions between water and minerals in concrete. Abrasion is mechanical damage caused by scratching or rubbing from vehicles or sharp objects; combined with solid particles like sand, it leads to wear defects. A slippery surface is characterized by excessive smoothness, which is dangerous and indicates a poor condition that should be fixed as soon as possible [24]. Stains can have different colors, shades, and textures. The main types include biological growth stains (e.g., fungi, beetle), dust stains, chemical reaction stains, corrosion stains, and water stains [25,26]. Other types of concrete surface defects are bugholes, and flatness defects. Bugholes are small holes formed by air entrapment in fresh concrete [27]. Flatness defects are characterized by deviations in elevation and irregularity of the surface [28].

2.1.2. Inspection Methods

Various methods can be used to inspect concrete surfaces. Computer vision methods detect anomalies in the collected data [29]. Crack measuring measures the characteristics of a crack on the concrete surface. Concrete cover measurement is essential for evaluating the depth of reinforcement within concrete, as inadequate cover can lead to premature corrosion and structural weaknesses. Magnetic field measurement complements this process by providing a non-invasive method to detect rebar positioning and alignment. Tools like magnetometers are used to measure variations in the magnetic field, offering insights into rebar alignment and identifying weak spots in concrete cover. These measurements contribute to ensuring structural integrity and preventing rebar-related defects [30].

Table 1. Common types of concrete surface defects based on Ontario inspection manual (adapted from [18]).

Surface Defect Types	Severity (All Dimensions in mm)			
Crack	Hairline (Width < 0.1)	Narrow (0.1 ≤ Width ≤ 0.3)	Medium (0.3 < Width ≤ 1.0)	Wide (1.0 < Width)
Spalling	Light (Any direction < 150 or depth < 25)	Medium (150 ≤ Any direction ≤ 300 or 25 ≤ depth ≤ 50)	Severe (300 < Any direction ≤ 600 or 50 < depth ≤ 100)	Very severe (600 < Any direction or 100 < depth)
Delamination	Light (Any direction < 150)	Medium (150 ≤ Any direction ≤ 300)	Severe (300 < Any direction ≤ 600)	Very severe (600 < Any direction)
Scaling	Light (depth ≤ 5 without exposure of coarse aggregate)	Medium (5 < depth ≤ 10 with exposure of some coarse aggregates)	Severe (10 < depth ≤ 20 with aggregate particles standing out from the concrete and a few completely lost)	Very severe (Depth > 20)
Disintegration	Light (Depth ≤ 25 with some loss of coarse aggregate)	Medium (25 < depth ≤ 50 with considerable loss of coarse aggregate and exposure of reinforcement)	Severe (50 < depth ≤ 100 with substantial loss of coarse aggregate and exposure of reinforcement over a large area)	Very severe (100 < depth and extending over a large area)
Erosion	Light (Depth ≤ 25 with some loss of coarse aggregate)	Medium (25 < depth ≤ 50 with considerable loss of coarse aggregate and exposure of reinforcement)	Severe (50 < depth ≤ 100 with substantial loss of coarse aggregate and exposure of reinforcement over a large area)	Very severe (100 < depth and extending over a large area)
Honeycombing	Light (depth ≤ 25)	Medium (25 < depth ≤ 50)	Severe (50 < depth ≤ 100)	Very severe (100 < depth)
Pop-Outs	Light (depth ≤ 25)	Medium (25 < depth ≤ 50)	Severe (50 < depth ≤ 100)	Very severe (100 < depth)
Cold joints	N/A			
Segregation	N/A			
Stratification	N/A			
Efflorescence	N/A			
Exudation	N/A			
Incrustation	N/A			
Stalactite	N/A			
Abrasion/wear	N/A			
Slippery surface	N/A			
Stain	N/A			

Moisture/humidity measurement is another method for inspecting concrete surfaces [31]. Infrared thermography uses a thermal camera to measure the temperature of concrete surfaces [32]. Since many humidity measurement tools rely on environmental features like temperature, devices such as thermo-hygrometers are commonly used to measure both air temperature and humidity. The rubber hammer test is a secondary inspection method used after a visual inspection to identify delamination or hollow areas in concrete. Tapping with a rubber hammer produces a distinct sound when defects like delamination are present, helping to confirm structural integrity beyond what is visible. Colorimetric test strips are a tool to identify the types of salts on the concrete surface [33]. The surface absorption test evaluates the absorption properties by measuring the amount of water that penetrates the concrete sample [34]. The half-cell potential test assesses the likelihood of corrosion in the reinforcement and concrete [35].

2.1.3. Causes of Defects

Maksymowicz et al. [36] proposed a basic taxonomy of mechanisms for the causes of the damages to concrete bridges and classified them into the following three main categories: chemical, physical, and biological mechanisms. Each of these mechanisms has some consequences, which can result in unique damages (e.g., losses, deformations, displacements, etc.).

Concrete surface defects can appear for a variety of reasons. The primary issues that might produce defects on concrete surfaces during the design phase are poor design and design-related errors. Some instances of poor design include: (1) Improperly designed formwork, which affects the shape of the surface and can lead to defects; (2) Incorrect design of expansion joints and inappropriate material selection, causing surface defects; and (3) Improper selection of release agents, leading to defects such as stains [37].

Main construction-phase problems leading to surface defects include: (1) Using defective or incorrectly utilized formwork; (2) Inappropriate transportation reducing concrete quality, causing defects like cracking and segregation; (3) Incorrect water content in the mix can lead to defects like surface cracking [38,39]; (4) Improper casting practices or casting in unsuitable weather conditions can also cause defects. For example, scorching temperatures during placement can lead to rapid evaporation of moisture from the concrete surface, causing premature hardening. Sustained exposure to very high temperatures can impair the internal curing process, reducing overall strength. Both conditions ultimately contribute to surface defects [40,41]; (5) Incorrect placement of casting joints leads to deformation and surface defects; (6) Improper compaction results in defects like honeycombing and bugholes [42]; (7) Concrete requires adequate curing time under suitable humidity and temperature to achieve desired durability. Inadequate curing can lead to surface cracks; (8) Reinforcement that is properly positioned but not secured or aligned correctly can result in poor performance and surface defects due to inadequate anchoring or integration with the surrounding concrete; (9) Lack of sufficient concrete cover on the reinforcement causes the reinforcement to corrode, resulting in surface defects [43]; (10) Incorrect application of the release agent can cause surface stains; (11) Lack of supervision and unskilled workmanship contribute to surface defects.

During the operation phase, surface defects can be caused by: (1) Environmental problems due to changes in temperature, humidity, and moisture, which can cause various factors (e.g., thermal stress) that play a role in forming surface cracks [44]; (2) Exposing concrete to fire can cause changes in the microstructures and defects such as cracks and delamination [45]; (3) Chemical mechanisms such as acid reactions, alkali-aggregate reactions, carbonation, chloride penetration, creation of composing salts, leaching, oil and fat influence, and sulfates reactions [36]; (4) Biological degradation mechanisms involve the accumulation of contamination and living organism activity; (5) Corrosion and expansion of reinforcement, often influenced by environmental factors, cause surface defects during operation [46]; (6) Abrasion, causing wear through loss of concrete mass from impact, friction, or traffic, leads to surface defects [18,47]; (7) Physical degradation mechanisms include creeping, shrinkage, material fatigue, extreme temperature influence, freezing actions, foundation displacement, and overloading [36]; (8) Load problems include static and dynamic over-loading, excessive vibration, and stress concentration that can lead to surface defects [48]; (9) Changes in concrete properties, such as creep and shrinkage, can cause settlement or deformation, leading to surface defects [49,50]; and (10) Vandalism is also a cause of surface defects during the operation phase [51].

During the maintenance phase, problems such as lack of maintenance and insufficient frequency of applying surface protection will cause aging deterioration and, consequently, concrete surface defects [52,53].

Diagnosis methods to find the causes of concrete surface defects include: (1) Remote-sensing-based diagnosis uses methods such as thermal imaging and LiDAR to analyze inspection results, identifying concrete surface anomalies and structural issues; (2) Magnetic-based diagnosis examines magnetic force data, rebar location, and cover thickness to detect corrosion and other defects, using methods like concrete cover measurement [54]; (3) Acoustic-based diagnosis analyzes sounds produced during tests, such as the rubber hammer test to detect early defects [55]; (4) Moisture/humidity-based diagnosis assesses absorption and humidity data to determine concrete porosity, using methods like the initial absorption test; (5) Chemical-based diagnosis detects harmful substances using methods like colorimetric strips, identifying defects they cause on the concrete surface; (6) Electrochemical-based diagnosis assesses corrosion probability using methods like the half-cell potential test [56].

2.1.4. Condition Assessment

According to OSIM [18], the severity and type of concrete surface defects are used to assess the condition of structural elements. Medium cracks on the concrete surface indicate a fair condition, while wide cracks signify a poor condition. Spalling, regardless of severity, represents a serious issue and denotes a poor condition that requires immediate corrective action. Similarly, delamination, disintegration, or erosion, at any severity level, indicate a poor condition. Severe or very severe scaling, honeycombing, or pop-outs also classify the element's condition as poor.

In contrast, the presence of defects such as cold joints, segregation, stratification, efflorescence, exudation, incrustation, stalactites, abrasion damage, or wear, as well as a slippery surface, suggests a fair condition.

Concrete element conditions are categorized into four levels: excellent, good, fair, and poor. Excellent condition applies to newly constructed elements with no surface defects or required treatment. Good condition is characterized by minor, non-functional defects that do not necessitate corrective action. Fair condition involves moderate defects where preventive or corrective measures, such as applying protective surface coatings, may be cost-effective. Poor condition describes severe defects that compromise performance, requiring significant treatment measures like rehabilitation or replacement.

2.1.5. Repair, Rehabilitation, and Replacement

The 3R actions help to extend the actual useful life of a structure after the formation of defects or damages caused by defects. ISO (International Organization for Standardization) [57] provides a framework and fundamental principles for the maintenance and repair of existing concrete structures. The 3R methods to deal with minor concrete surface defects are: (1) Surface cleaning to remove water, dirt, debris, and stains from concrete surfaces [58]; (2) Irregularities related to non-flatness (bulge, roughness, waviness) can be repaired by methods such as surface grinding. Since excessive grinding also weakens the concrete surface, this issue should be considered when using this method [59]; (3) Protecting protruding edges is a preventative method to protect the protruding edge of concrete surfaces from defects [37]; (4) Using surface sealing or coating compounds, a preventative action, stops the penetration of water and other destructive chemicals into the concrete surface, reducing damage from chemical reactions and rebar corrosion. The difference between surface sealers and surface coatings is that sealers penetrate the surface and are applied in thin layers, whereas coatings form a thicker layer on top of the surface (e.g., epoxy sealer, silicone sealer). The materials used for sealing and coating compounds have a wide variety of choices [60].

The 3R methods to major repair or replacement of defective concrete include: (1) Excessive corrosion of the rebar weakens the strength and causes defects such as surface cracks. In such cases, to strengthen the concrete, the corroded parts are removed and replaced with new rebar [61]; (2) When concrete needs strengthening, fiber-reinforced polymers (e.g., glass fibers, steel fibers) can be used [62]; (3) To repair or replace concrete, measures include detaching and removing loose parts and adding a new layer of concrete; (4) Curing is performed for the added or replaced concrete to maintain the appropriate humidity and temperature conditions at depth and at the surface, which plays a vital role in developing the strength and durability of concrete [63]; (5) Resin injection is a method to repair defective concrete. Some types of penetrating surface sealers (e.g., polyurethane) can be used for this purpose [64]; (6) In the shotcrete method, concrete or mortar is projected onto the surface at high velocity, allowing placement of high-strength, low-permeability concrete without the need for forms [65]; (7) Conventional mortar or concrete, composed of water, cement, and aggregate, can repair or replace defective surface parts [66]; (8) Preplaced aggregate concrete consists of compacted coarse clean aggregates, followed by cement grout injection. Because of the grout's high fluidity, forms must withstand higher fluid pressure than in conventional concrete to prevent leakage during grouting. This method can be used to repair or replace defective concrete surfaces [67]; (9) Polymer-modified mortar or concrete combines polymer additives with cement and aggregate, requiring less water than conventional concrete. In contrast, polymer concrete mortar consists of only polymer and aggregate. This mortar or concrete offers high strength, adhesion, and density while reducing permeability and shrinkage [68,69]; and (10) Epoxy mortar or concrete is made from a combination of epoxy and sand or epoxy, sand, and coarse aggregate. This mortar or concrete has characteristics to protect the rebar against corrosion [70].

Current approaches to inspecting and maintaining concrete surfaces face challenges due to subjectivity and inefficiency. To take appropriate 3R actions, defects must be accurately identified, and the characteristics of each defect considered to determine proper future actions [25].

2.2. Inspection and Repair Information Modeling

Several studies explored extending BIM for Inspection and Repair Information Modeling (IRIM). For example, in facilities management, Hassanain et al. [71] developed an integrated maintenance management prototype that demonstrated the potential uses of IFC to improve interoperability in the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry.

Defects are considered in two different phases of the lifecycle of infrastructure facilities: the construction (or manufacturing) phase and the O&M phase. In the construction phase, defects are caused by errors or imperfections in the construction. In the O&M phase, defects are caused by factors such as loads applied on the structure, environmental effects, and natural aging. Although the causes of surface defects can be very different in these two phases, there are important similarities that can be exploited in developing IRIM from the point of view of type of defects (e.g., cracks, spalling) as well as the inspection processes and methods.

2.2.1. IRIM in the Construction Phase

Park et al. [72] proposed a framework for construction defect management using a BIM and ontology-based data collection template. Wang et al. [73] estimated the dimensions of the precast concrete elements using LiDAR and compared it with as-designed BIM as a reference. Kim et al. [74] introduced a systematic approach for assessing the dimensional and surface quality of precast concrete elements, utilizing BIM alongside advanced spatial measurement technologies for enhanced precision and reliability. The proposed IFC-based entity-relationship model for the precast concrete element quality inspection is rather simple and does not cover all the details needed for modeling the defects information in a comprehensive way. For example, the location of the defects is represented using ifcDirection, which is obviously not enough to specify the location of the defect on the 3D model of the structure.

2.2.2. IRIM in the O&M Phase

Aruga and Yabuki [75,76] proposed a cooperative management model for structures in the O&M phase. The maintenance management framework considers both the degradation level (i.e., condition assessment) and the measured values (i.e., inspection results). The evaluation based on inspection includes identifying the probable cause of the defect and predicting its future progress. Furthermore, the framework of the degradation and measured values includes several inspection data types (e.g., sketch, photo, drawings) that could be used to identify the shape and location of the defects. However, this research did not discuss all the details of the IRIM.

Kasireddy and Akinci [77] proposed integrating inspection data with IFC-Bridge. The advantages of this model are using IfcRepresentation and several contexts for representing the geometry of a defect from multiple inspections and using extended relationships from the IFC and IFC-Bridge to link bridge element information with condition information. They stated that one limitation of their approach is that they used some classes from the present version of IFC-Bridge to represent other classes required for a condition assessment. Hammad et al. [78] presented a conceptual framework that integrates all lifecycle data into a 4D model of a bridge. This model enables the correlation of spatial and temporal dimensions to provide a comprehensive view of the bridge lifecycle. Motamedi et al. [79] introduced a model to categorize various defect types and establish links between building components and associated defects, as well as the workflows for their inspection, assessment, and remediation. By extending the IFC schema, their approach incorporated additional elements needed for the systematic representation of defect information within BIM. However, they did not investigate an ontology related to inspection and repair modeling. Choi et al. [80] proposed a framework to enhance building maintenance by integrating visualized inspection data with BIM using 3D point clouds. Their method processes laser-scanned data to extract precise defect details, improving inspection reliability and efficiency. Similarly, Tan et al. [81] introduced a BIM-based defect data management system that organizes and updates real-time inspection information. This platform provides comprehensive oversight for managing building inspections and repairs throughout the building's lifecycle.

Chen et al. [82] developed a product model for harbor structure degradation. One of the main contributions of this work is that defects are classified according to the following types: surface degradation (e.g., change in color), addition degradation (e.g., corrosion), subtraction degradation (e.g., cracks), deformation, and material deterioration. However, this research focused on the defect modeling for harbor structures and did not attempt to provide a general approach for IRIM.

The most related previous studies are summarized in Table 2, including whether or not the following information is included in the studies: (1) the inspection process; (2) the diagnosis process; (3) the 3R process; (4) using BIM for defect product modeling; and (5) using conceptual model (i.e., ontology) in the process. In most of these works, semantic description (i.e., ontology) was not considered (except [83]). Hamdan et al. [83] created a Concrete Damage Ontology (CDO) focusing on certain concrete structural damages. They also developed a separate ontology for structural damage assessment, guided by the German "Instruction of Road Information Databases for Constructions". This assessment aimed to identify factors for evaluating the impact of damage on structural health, durability, and traffic safety. However, the ontology they used for this purpose is not publicly accessible and relies on German terminology. Furthermore, Hamdan et al. [83] did not develop ontologies for inspection processes and the 3R (Repair, Rehabilitation, and Replacement) approach. Their ontologies were neither unified nor comprehensive, lacking in capturing all necessary semantic relationships for effective modeling. Additionally, their damage assessment ontology was specific to road construction and not adaptable to different types of structures.

Table 2. Summary of related works to IRIM.

Paper	Year	Type of Defect	Process			Defect Modeling	Ontology
			Inspection	Diagnosis	3R		
Dynamic graph CNN based semantic segmentation of concrete defects and as-inspected modeling [84]	2024	Crack, Spalling	✔	-	-	✔	-
Damage volumetric assessment and digital twin synchronization based on LiDAR point clouds [85]	2024	Crack	✔	-	-	✔	
A BIM Based Framework for Damage Segmentation, Modeling, and Visualization Using IFC [86]	2022	Spalling	-	-	-	✔	-
A semantic modeling approach for the automated detection and interpretation of structural damage [83]	2021	Structural damages (Concrete inhomogeneity, Crack, Spalling, Chemical damage, Moisture damage, Reinforcement damage, Tendon damage)	✔	✔	-	✔	✔
Modeling geometry and semantics of physical damages using IFC [87]	2020	Crack, Spalling	-	-	-	✔	-
Bridge damage: Detection, IFC-based semantic enrichment and visualization [88]	2020	Spalling	✔			✔	
A generic model for the digitalization of structural damage [89]	2018	Non-specific structural damages	-	-	-	✔	-
Integrating RC bridge defect information into BIM models [90]	2018	Crack, Spalling, Scaling, Efflorescence, Rust staining, Abrasion/Wear, Exposed reinforcement	-	-	-	✔	-
SeeBridge as next generation bridge inspection: overview, information delivery manual and model view definition [91]	2018	Crack, Spalling, Scaling, Efflorescence, Rust staining, Abrasion/Wear	✔	-	-	✔	-
Bridge Information Modeling based on IFC for supporting maintenance management of existing bridges [92]	2018	Non-specific defects	✔	-	✔	✔	-
Bridge Information Modeling based on IFC standards and web content providing system for supporting an inspection process [93]	2016	Non-specific defects	✔	-	-	✔	-
Information modeling of earthquake-damaged reinforced concrete structures [94]	2015	Cracks, Structural damages (Braking, Buckling)	-	-	-	✔	-

2.2.3. Limitations of Previous Research Related to IRIM

Based on the review, despite the great benefits of the previous research related to IRIM, it has the following limitations:

(1) Duplication of efforts: Different researchers have focused on IRIM related to different types of civil infrastructures (e.g., bridges or tunnels), different types of material/elements, or at different phases of the lifecycle (e.g., construction or O&M). For example, comparing the models proposed by Chen et al. [82] for harbor concrete structures, Kasireddy and Akinci [77,95] for bridges, and Kim et al. [74] for precast concrete elements, it can be seen that they used very different levels of detail for representing the properties of defects (e.g., location and geometry). This will result in the duplication of efforts and less efficient research progress.

(2) Ad hoc and shallow representation of concepts: One common aspect of most of the previous research works related to IRIM is that they focus on mapping a rudimentary

data structure of the IRIM processes and products to the entities available in IFC or its derivatives (e.g., IFC-Bridge). This approach results in rather ad hoc and shallow models because not all the required entities are available in the current version of IFC. On the other hand, when new entities are added, researchers add different entities that are duplicated but use variant terms. For example, the terms 'degradation' and 'defect' are used to represent the same concept.

(3) Limitations related to information modeling: Several researchers have discussed the link between the physical measurements of defects in the inspection process and the resulting condition assessment (or severity evaluation) in the diagnosis process, and the following decisions about the 3R actions. However, most of the previous research focused only on the modeling of defects. Therefore, more research is needed for modeling the other aspects of inspection, diagnosis and 3R information.

(4) Lack of comprehensive modeling: Some of the previous research focused on a specific inspection technology and the IRIM was developed only to demonstrate that technology (e.g., Kim et al. [74]).

2.3. Ontology Approach

One of the most widely used definitions of ontology is explicit shared knowledge and conceptualization of the domain [96,97]. Gaševic et al. [98] describe ontology as encompassing two key elements: a domain-specific vocabulary and a knowledge representation framework utilizing this vocabulary for domain description. In essence, an ontology represents relationships among a set of concepts, formally expressed as shown in Formula (1) [99].

$$\Omega = \{C, R\} \tag{1}$$

where Ω denotes the ontology, C represents the set of concepts, and R defines the relationships connecting these concepts. Various tools and languages exist for ontology development, such as Protégé [100] and OntoEdit [101], which serve as prominent examples of ontology editing environments [102]. Protégé offers plugins facilitating the visualization and editing of ontologies. Meanwhile, the Web Ontology Language (OWL) and Resource Description Framework (RDF) enable the representation of ontologies in both human- and machine-readable formats [103], allowing for the depiction of intricate interrelationships among ontology concepts [104].

OWL provides the ability to describe complex concepts based on simpler ones available in the ontology. It has a reasoner that can be used for checking the consistency of the concepts defined in the ontology. Ontologies typically can be developed as XML-based files and can be represented in a computer using logic languages such as Knowledge Interchange Format (KIF) [98]. KIF is like the First Order Logic (FOL) and can provide the encoding of knowledge using a variety of logical operators.

Ontology-Based Knowledge in Construction

El-Diraby and Kashif [103] proposed a distributed ontology framework aimed at improving knowledge management in highway construction projects. This approach tackles the challenges of integrating diverse knowledge sources across multiple stakeholders. El-Gohary and El-Diraby [105] introduced an infrastructure and construction process ontology that offers a formal representation of the process knowledge in the infrastructure and construction domain. El-Diraby [106] presented a domain ontology of construction knowledge, which contains the conceptual architecture, relationships, and behaviors of the key terms in the construction domain. Park et al. [72] briefly discussed the benefits of developing an ontology for proactive construction defect management. Venugopal et al. [107] introduced an ontology-based framework to streamline information exchanges within the precast and prestressed concrete sector. Zeb and Froese [108] developed a structured ontology for transaction management, focusing on formalizing data exchanges in infrastructure management.

Cacciotti et al. [109] designed an ontology tailored to managing and diagnosing damage information, specifically addressing the needs of cultural heritage conservation. However, the detailed taxonomies for damages and the cause of damages were not developed in their ontology. Moreover, their approach was domain-specific, and it is not widely applicable for other types of construction domains [83]. Jung et al. [110] proposed an ontological approach to infer the causes of concrete cracks. However, their study was limited to the crack defect, and their proposed approach does not support BIM. Lee et al. [111] developed a linked data system framework for sharing construction defect information using ontologies and BIM environment. Niknam and Karshenas [112] introduced the BIM Shared Ontology (BIMSO) as a foundational framework and extended it with the BIM Design Ontology (BIMDO) to represent the design characteristics of building components. Kim et al. [113] proposed an ontology to integrate FM maintenance work information of traditional FM system database and BIM-based data. The Building Element Ontology (BEO) [114] and the Mechanical, Electrical, and Plumbing (MEP) ontology [115] are both derived from the IFC schema. These ontologies lack predefined relationships, allowing users to tailor their application to specific domain needs. Hamdan et al. [116] proposed Damage Topology Ontology (DOT), which is a small high-level ontology to describe any type of damage topology in general. Later, Hamdan et al. [83] proposed a small ontology called Concrete Damage Ontology (CDO) to define some damages in concrete structures. Rasmussen et al. [117] introduced the Ontology for Property Management (OPM), a streamlined, high-level ontology designed to track property changes and manage valuations over time. In another study, Rasmussen et al. [118] proposed Building Topology Ontology (BOT), which is a minimal ontology to describe building stories and space topology. Bonduel et al. [119] developed the Ontology for Geometry Formats (FOG), facilitating the exchange of descriptive geometric data. Similarly, Wagner et al. [120] created the Ontology for Managing Geometry (OMG) to bridge the gap between building components and their geometric representations. Bahreini and Hammad [121] developed OBRNIT, which is an ontology for BIM-based robotic navigation and inspection tasks.

3. Developing OCSD

The proposed method for developing OCSD is based on the following steps and using the general approach and tools discussed in Section 2.3 are: (1) defining the competency questions by analyzing the previous related research to identify the common aspects and limitations of available models. (2) identifying the steps for developing the ontology at a level of abstraction that can be applied to different structures/materials. (3) extending the basic ontology to cover all the requirements defined in Step 1.

3.1. Competency Questions for the OCSD

The competency questions are defined to clarify the requirements of the inspection, diagnosis, and 3R processes of concrete surface defects domain [122]. The following competency questions are defined for developing a unified ontology based on the reviewed literature and the limitations of previous research.

(1) OCSD should follow a top-down approach where the common aspects of defects are molded at a higher level so that they can be shared by several types of structures and used at different phases of the lifecycle. For example, reinforced concrete surface cracks are very similar in tunnels and bridges although they are caused by different types of loads. This modeling approach will not only avoid duplicating efforts but will also provide a better-quality model, which grasps the essence of IRIM and can be further extended to cover the specific details related to the specific type of structure and the phase of lifecycle.
(2) OCSD requires comprehensive modeling. OCSD should cover as much details as possible about the generic aspects of the inspection, diagnosis, and repair processes (i.e., process modeling) and the resulting defect model (i.e., product modeling). This

requires developing a clear taxonomy considering all the semantic relationships required for modeling.

(3) OCSD should satisfy the needs of the state-of-the-art infrastructure management systems and guidelines. OCSD should reflect the common aspects of guidelines at an abstract level that can be applied to the widest category of structures. On the other hand, it is expected that the product and process models that can be developed based on the OCSD will influence the current infrastructure management practices by creating an opportunity to re-engineer the processes used in these systems and enhancing additional aspects of IRIM in these systems (e.g., defect modeling).

(4) OCSD should not be restricted to the resources available in the current modeling standard (i.e., IFC). In other words, OCSD can be used as a starting point to extend IFC. Therefore, before extending any BIM-based standard (i.e., IFC) for inspection purposes, it is necessary to understand the defects and inspection-related concepts at the abstract level.

(5) OCSD should have the ability to accommodate new data collection technologies. The amount of inspection data is expected to grow exponentially with the availability of new technologies (e.g., LiDAR, photogrammetry, etc.). OCSD should support these technologies and provide the means to accommodate the collected raw data and the resulting inspection information.

3.2. Methodology Workflow

This section explains the main steps for developing an Ontology for Concrete Surface Defects. OCSD development methodology is METHONTOLOGY. METHONTOLOGY is a clear, mature, and well-documented method [123,124].

As shown in Figure 1, the initial, development, and final stages are three main steps of ontology development in METHONTOLOGY. The best practices and knowledge in the inspection, diagnosis, and 3R processes of the concrete surface defects domain are used to develop OCSD.

Determining the scope and main concepts and taxonomies of OCSD are the steps that should be considered in the initial stage. The scope of OCSD is defined based on the competency questions defined in Section 3.1. Moreover, the required level of covered details and the size of development will be considered in this step. In the step of defining concepts and taxonomies, the related knowledge to OCSD is gathered based on literature from many sources such as textbooks, research papers, and online resources. At all steps of this stage, communication with end-users and professionals and receiving feedback are essential. The list of requirements not only helps in the defining scope step but also helps in other stages of development.

Constructing and verifying the initial structure of OCSD are considered in the development stage. The first step of this stage uses a formal language (e.g., OWL) to implement and represent the conceptual model. The formal language helps the ontology to be easily used by different systems [125]. Based on the availability and maturity level of ontologies and to fulfill the competency questions defined in Section 3.1, OCSD is developed from scratch. In the next step of the development stage, ontology verification is technically examined based on the developed ontology's consistency checking and competency questions.

The final stage involves improving OCSD through experts' and end-users' suggestions and real-world needs. Criteria-based evaluation method is used to evaluate OCSD. The entire ontology development life cycle involves knowledge acquisition, evaluation, and documentation. The final step is documenting the developed OCSD. The IDEF5 (Integrated DEFinition) [126] ontology description method is used to present the details of input, output, control, and mechanism in each of the methodology steps.

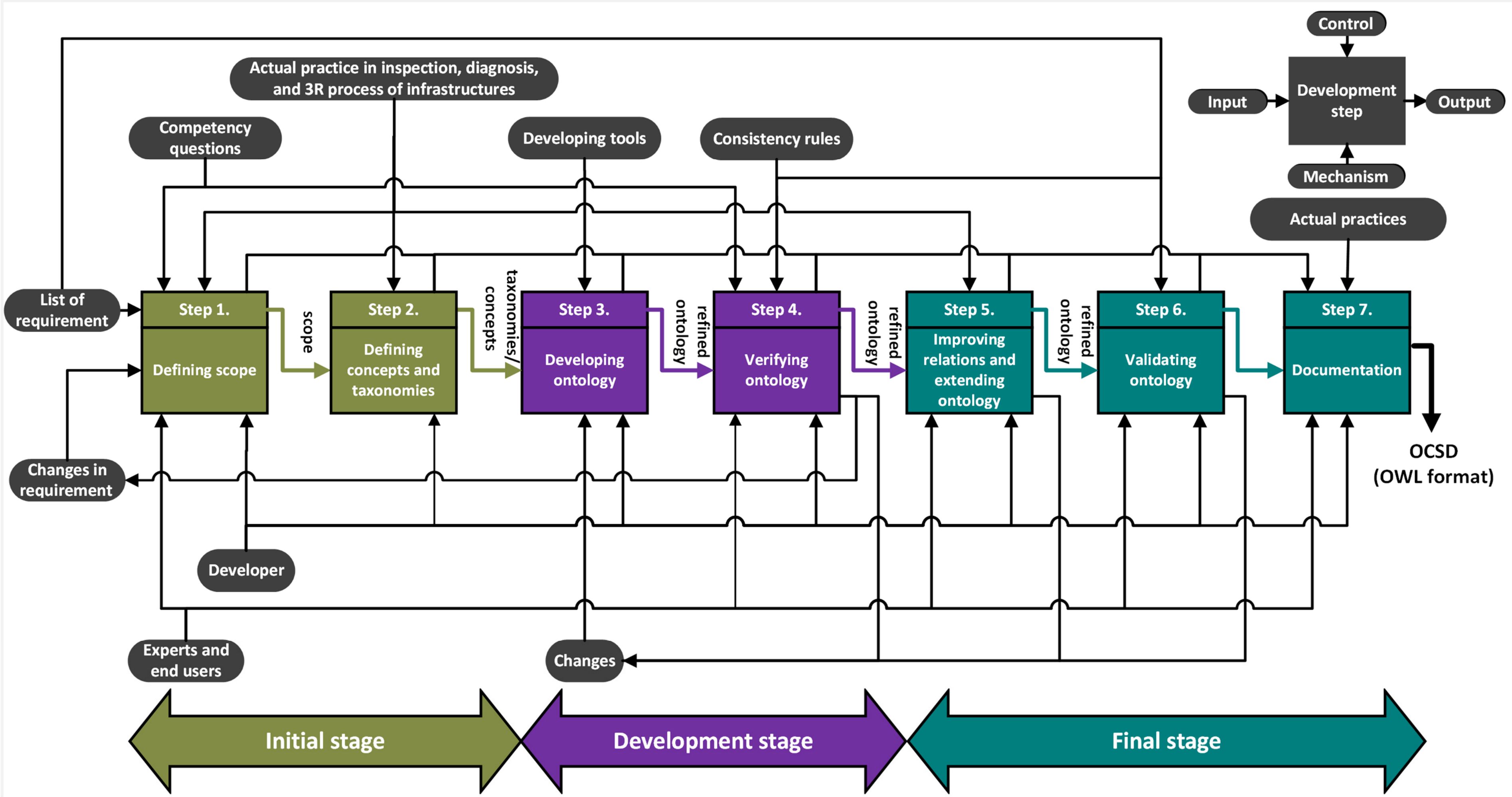

Figure 1. Development workflow of OCSD (adapted from Taher et al. [127].

3.3. Components of OCSD

A few concepts from CDO [83], which is a small ontology and mainly developed for concrete structural damages, are used as parts of this study. The following components represent the main concepts that should be included in the unified ontology. Some of these concepts are extracted from previous research, while others are added to satisfy the competency questions of the ontology. OCSD is developed using Protégé [100]. OCSD has 335 classes, 51 relations, 27 attributes, and 31 individuals. The current version of OCSD is available at https://github.com/OCSD-OWL/OCSD (accessed on 18 October 2024).

OCSD covers five main groups of concepts related to process and product modeling, including: (1) inspection concepts, (2) diagnosis concepts, (3) 3R concepts, and (4) defect concepts, which are explained in the following sections. Figure 2 shows the main types of OCSD concepts. The concepts of ontology are semantically interrelated by the relationships defined between concepts. The types of relations used in OCSD are: is (e.g., point cloud is collected data), has (e.g., inspection process has target), uses (e.g., remote sensing method uses LiDAR), captures (e.g., image sensor captures image), performs (e.g., inspector performs inspection process), causes (e.g., temperature change causes thermal stress), affects (e.g., environmental problem affects reinforcement expansion), analyzes (e.g., crack monitoring analyzes crack dimension), evaluates (e.g., condition assessment evaluates extent of damage), determines (e.g., condition assessment determines condition), depends on (e.g., condition depends on severity), treats (e.g., 3R process treats host element), chooses (e.g., 3R process chooses repair material), and includes (e.g., reinforcing polymer includes steel fiber).

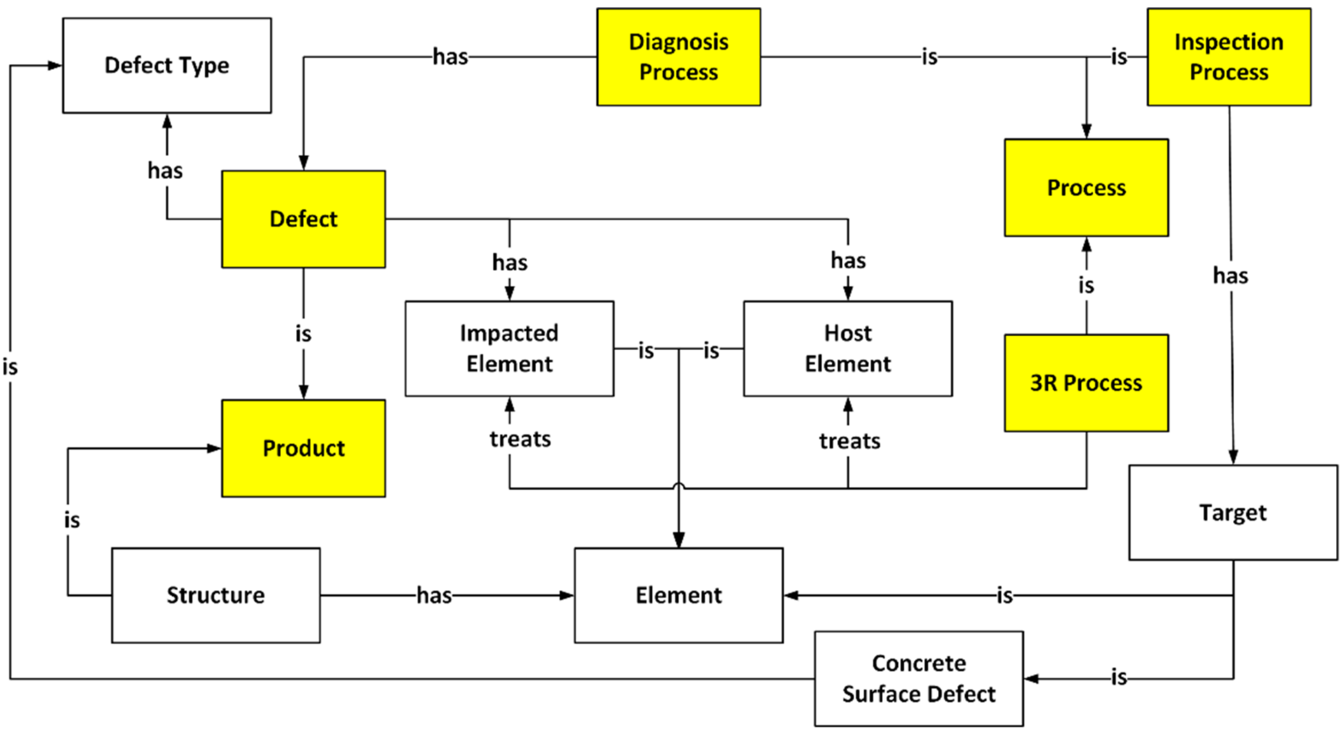

Figure 2. Main types of OCSD concepts (main entities marked in yellow).

3.3.1. Process Modeling Concepts

OCSD covers three main types of processes: (1) inspection concepts, (2) diagnosis concepts, and (3) 3R concepts, as explained below.

Inspection Concepts

Concrete surface inspection should be performed systematically and regularly to identify existing surface defects and detect possible future anomalies. The inspection concepts of OCSD cover the main concepts related to the inspection of concrete surface defects. Specific relationships are defined in OCSD to semantically interrelate different inspection methods and associated inspection results. Figure 3 shows the OCSD inspection process's main concepts and relationships. The inspection process has an inspection method, which can be visual inspection, testing, or a method for measuring defects.

The information of the inspector and inspection work schedule is covered in OCSD. Some concepts are duplicated in Figures 3–6 to improve the readability of the figures. Furthermore, the main concepts are marked in yellow.

The inspection method can be chosen based on the order of complexity. As explained in Section 2.1.2, Measurement methods for the inspection of concrete surface defects are remote sensing methods (e.g., LiDAR), health monitoring (e.g., fiber-optic sensors), or methods to measure defects (e.g., crack), magnetic field, and environmental conditions (e.g., temperature, moisture, humidity). Concrete cover measurement is primarily achieved through magnetic field measuring, using tools like magnetometers to evaluate cover depth by detecting rebar positioning. Other methods, such as ultrasonic testing, may also be employed in specific scenarios, reflecting the versatility of inspection technologies for evaluating structural integrity. Beyond measuring concrete cover, magnetic force information can also identify structural inconsistencies, such as improper rebar placement or voids, through variations in magnetic readings. For instance, these variations might highlight anomalies like misaligned reinforcement or embedded defects, extending the diagnostic potential of magnetic measurements.

The collected data depend on the inspection method. For example, a visual inspection will produce images, and an inspection using LiDAR will produce point clouds. Post-processing of inspection data includes Edge detection, shape extraction, and clustering. Computer vision methods, such as image processing and machine learning, automate the detection and analysis of surface irregularities, cracks, and anomalies, reducing manual effort and enhancing accuracy, especially for large-scale infrastructure assessments. Inspection tools (e.g., binoculars [128]) and measurement devices are being used during the inspection to accomplish the process. Binoculars are occasionally used in preliminary visual inspections to scan for large or obvious defects in tall structures or hard-to-reach areas before conducting closer inspections. Measurement devices for inspection include image sensors (e.g., RGB, camera), LiDAR scanners, etc. Several devices can be used for crack measuring, including crack measuring magnifiers, crack width meters, vibrating wire crack meters, crack monitor gauges, crack measuring microscopes, and digital strain gauge deformation meters [129].

Testing includes destructive, semi-destructive, or non-destructive testing. Moreover, safety-related testing is mainly used to determine the serviceability of existing or repaired concrete elements. As discussed in Section 2.1.2, the testing methods that can be used for the inspection of concrete surface defects include the rubber hammer test, half-the cell potential test, the initial surface absorption test, and colorimetric test strips. Each of the measurement methods and inspection tests has a result that will be used in the diagnosis process. At the end of the inspection, the inspector will prepare an inspection report. Inspection frequency is another important factor that can help to detect the defects at an early stage. The inspected data can be archived in a time series format that allows easy retrieval and processing.

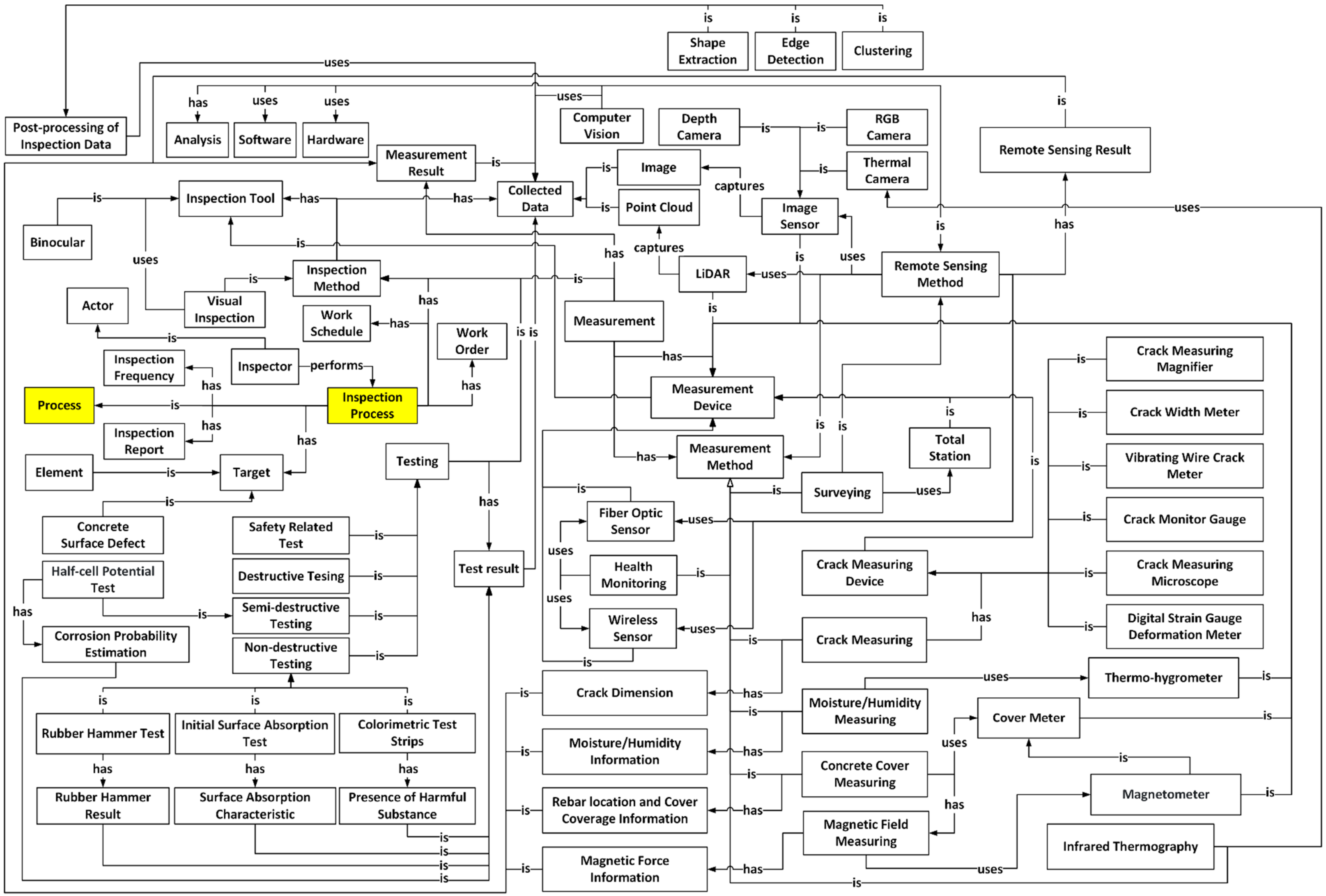

Figure 3. The main inspection process concepts and relationships (main entities marked in yellow).

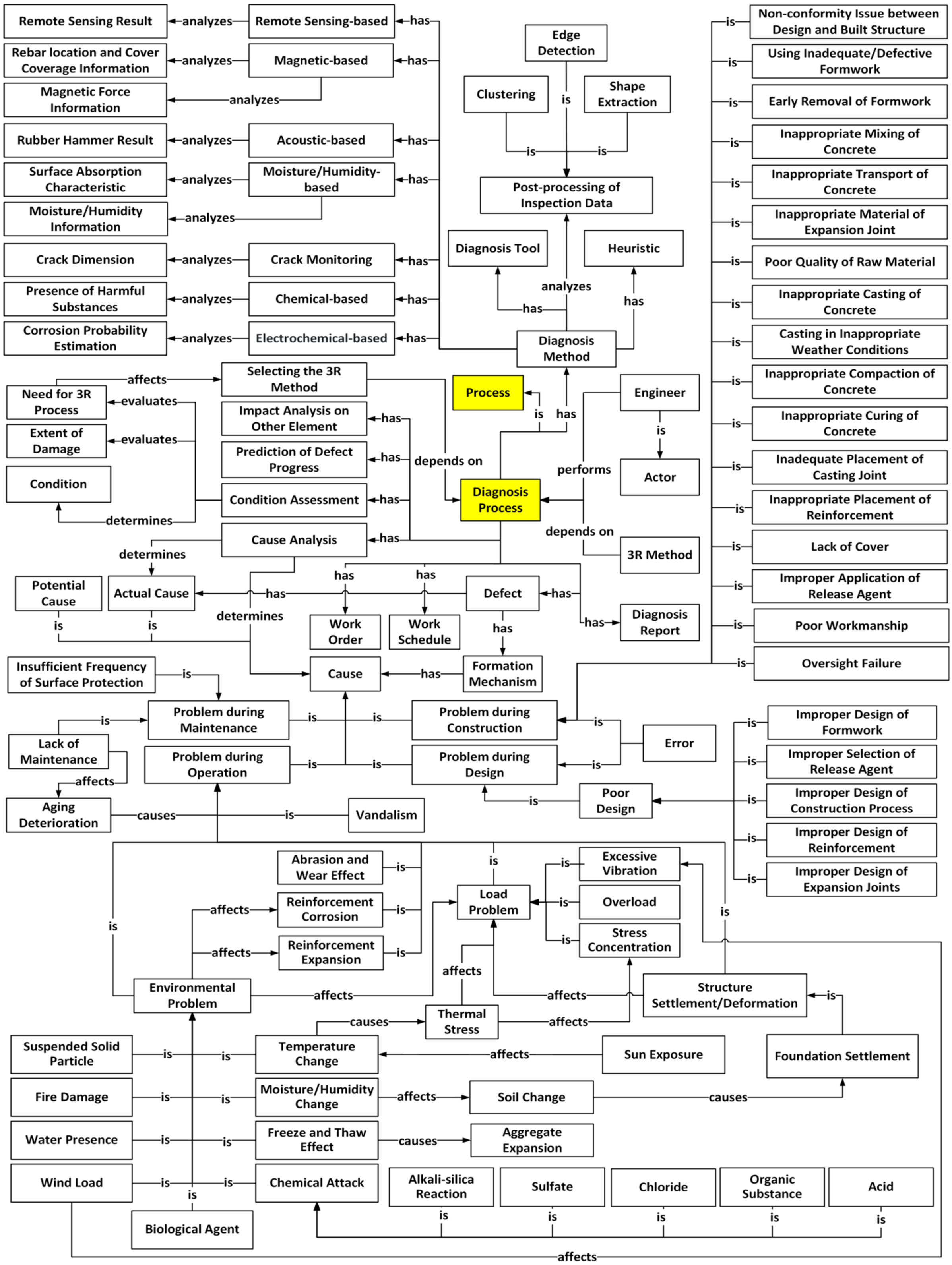

Figure 4. The main diagnosis process concepts and relationships (main entities marked in yellow).

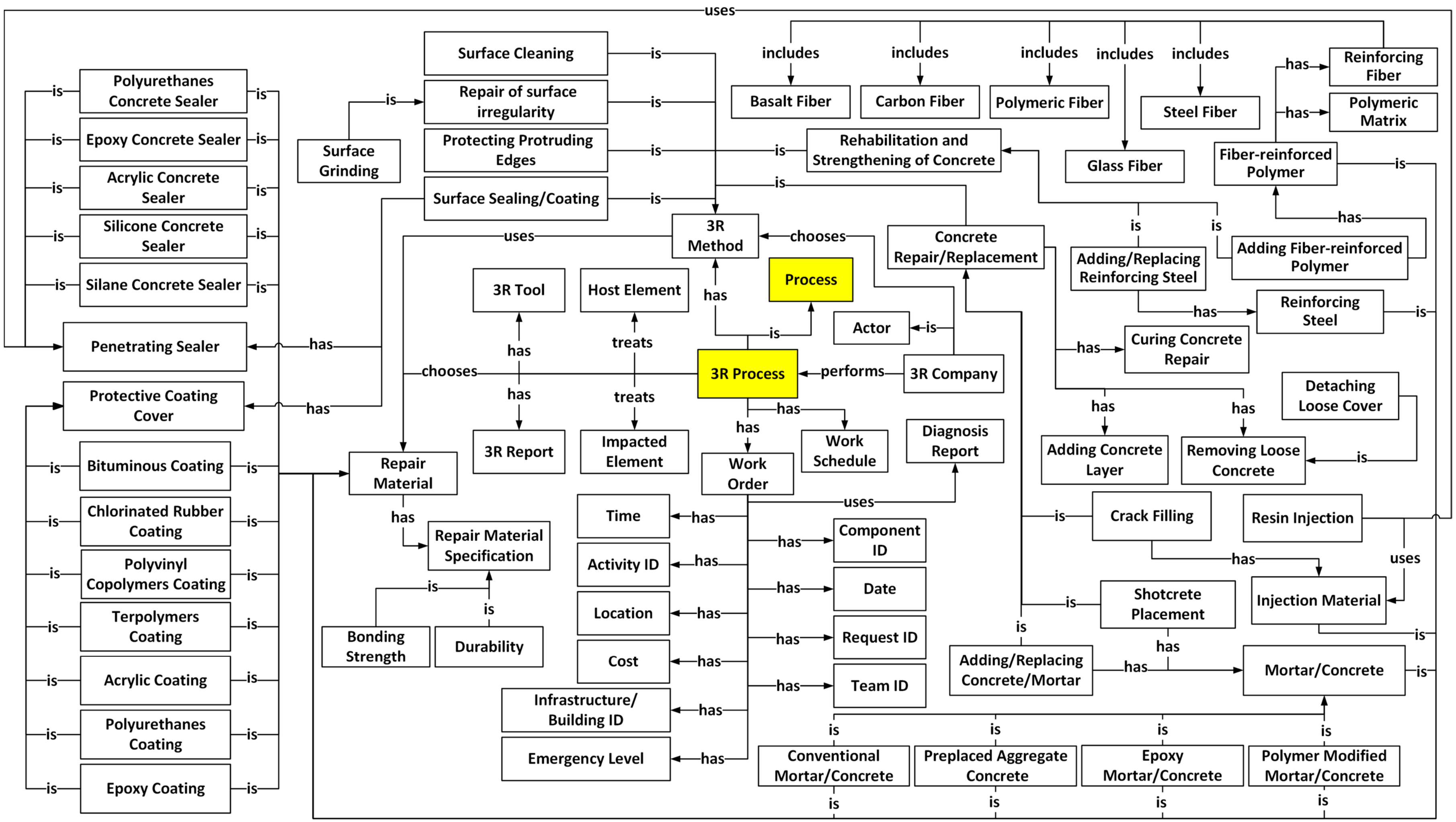

Figure 5. The main 3R processes concepts and relationships (main entities marked in yellow).

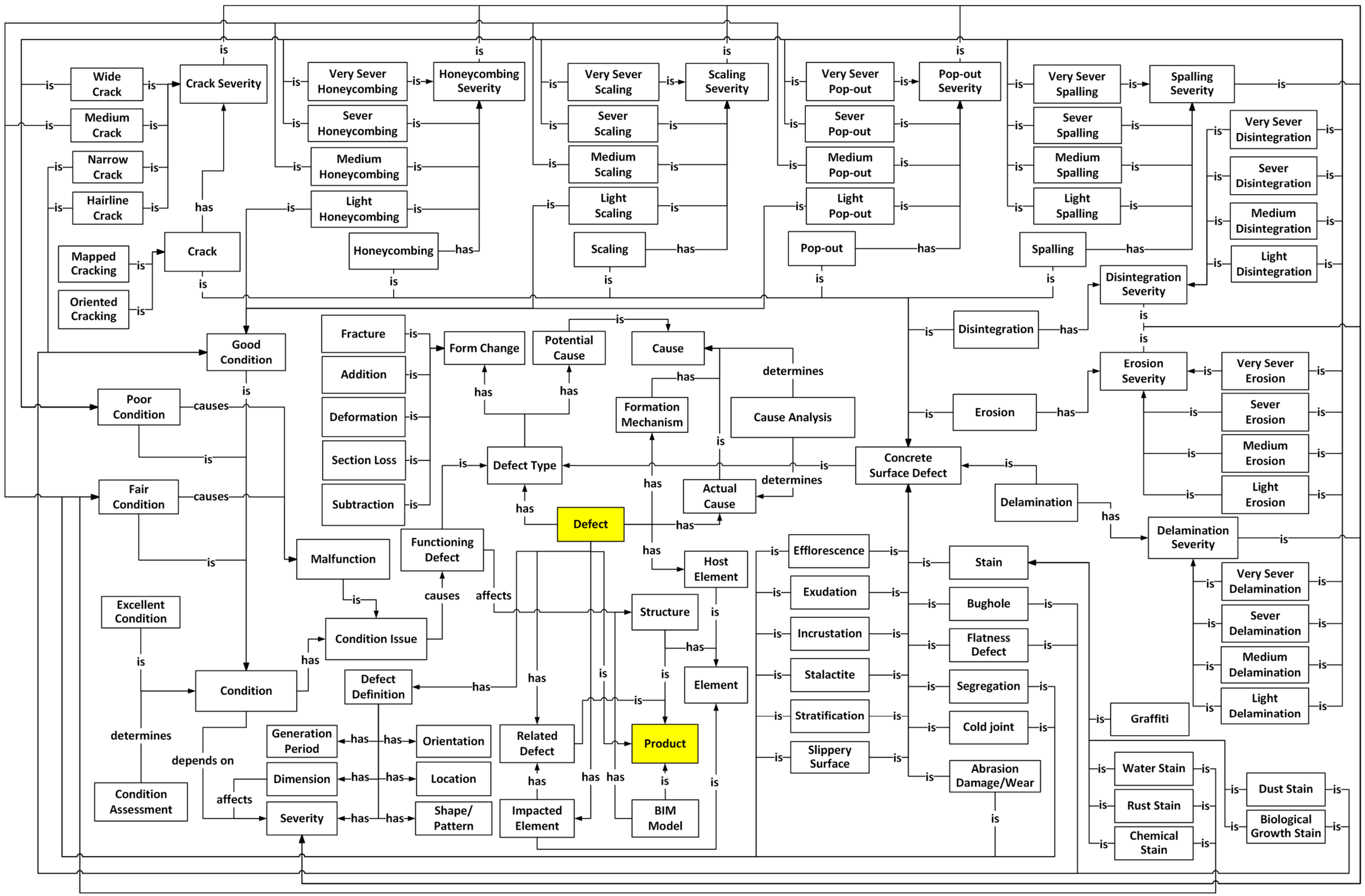

Figure 6. The main defects and the condition of the defective concrete surface concepts and relationships (main entities marked in yellow).

Diagnosis Concepts

The diagnosis process is an auxiliary process that evaluates the information obtained from the inspection. OCSD defines specific relationships to semantically link diverse diagnosis methods, cause analysis, and condition assessment. Figure 4 shows the OCSD diagnosis process's main concepts and relationships. The information of this process plays an important role in deciding the necessity of executing the 3R processes. The diagnosis process can be performed at the office by an engineer different from the inspector. Therefore, the information of the engineer needs to be covered in OCSD. The diagnosis process is based on processing the collected inspection data and the information about the surrounding conditions.

As shown in Figure 4, diagnosis concepts of OCSD cover concepts related to the analyzing the cause of the defect, predicting the defect progress, analyzing the impact of the defect on other elements of the structure and evaluating the extent of damage, assessing the condition of a concrete element based on inspection results, assessing the condition of connected elements based on gathered data from the surrounding environment [95], and evaluating the need for 3R processes.

The diagnosis process includes using tools and heuristic methods to interpret the inspection data. As discussed in Section 2.1.3, diagnosis methods will analyze the inspection results, whether remote sensing-based, magnetic-based, acoustic-based, chemical-based, etc., to find the causes of the defects.

OCSD covers various causes that have the potential to cause defects on the concrete surface. The appearance of the defect on the concrete surface has a formation mechanism. As discussed in Section 2.1.3, the formation mechanism of the defect is initiated by one or more causes [130]. The term *cause* encompasses all potential contributors that may initiate a defect's formation mechanism, including environmental factors, material properties, or design issues. The *actual cause* refers to the definitive root contributor, identified through detailed diagnostic processes. By distinguishing these terms, the OCSD model accounts for scenarios where multiple suspected factors interact, ensuring a structured progression from potential causes to the confirmed origin of the defect. Cause analysis considers the relationships with surrounding conditions, which can be reflected in the design, construction, operation, and maintenance phases.

As discussed in Section 2.1.3, the main problems during the design phase that can cause defects on the concrete surface include poor design of formwork, expansion joints, etc. The main problems during the construction phase that can cause surface defects include non-conformity issues between design and the built structure, inappropriate mixing, poor workmanship, etc. Non-conformity issues refer to design and built structure discrepancies concerning elements' attributes, such as location or dimensions. The main problems during the operation phase that can cause surface defects include environmental problems, load problems, etc. Lack of maintenance and insufficient frequency of surface protection are problems during the maintenance phase.

Surface defects are often the result of a combination of causes. For example, suspended solids, such as soil, dirt, debris, and fine sand, can accumulate on the surface, causing problems for the bonding coats. Eventually, coating problems allow water and chemicals to penetrate the surface and cause defects [131,132]. The presence of water, the effect of cycles causing aggregate expansion, attacks caused by the presence of chemicals (sulfates, chlorides), and biological agents such as microorganisms, fungi, etc., are factors that cause surface defects (e.g., cracks) [133,134].

At the end of the diagnosis process, the engineer will prepare a diagnosis report that includes information about the condition of the defect and the need for further actions and performing the 3R processes.

3R Concepts

In general, the term repair refers to restoring, renewing, or replacing the concrete surface or element after primary placement [135]. OCSD presents specific relationships to semantically link various 3R methods and related repair materials for defective components. Figure 5 shows the OCSD 3R processes' main concepts and relationships. In OCSD, repair refers to the specific actions that needs to be performed to treat the defective elements of the structure. Rehabilitation refers to the major repair of critical elements of the structure to reach the suitable service level. Replacement refers to the removal and replacement of defective areas or damaged elements of the structure. The 3R processes are based on the results of the diagnosis process and the condition of the defect, host elements, and impacted elements. After the diagnosis process, if further actions are required to maintain the element and the structure, the 3R processes will be performed to treat the element.

As shown in Figure 5, the 3R processes can be performed by a 3R company. The information of the 3R company and 3R work order are covered in OCSD. The 3R work order includes request and component ID, team or assigned person ID, date and time, location, estimated cost, status, and emergency level. The 3R processes include using material, tools, and methods to perform an acceptable level of concrete surface treatment. The quality-related specifications of materials, including bonding strength and durability of materials, are considered in OSCD. The 3R methods for treating concrete surface defects are surface cleaning, repair of surface irregularities, protecting protruding edges, surface sealing or coating, the rehabilitation and strengthening of concrete, and concrete repair or replacement as explained Section 2.1.5.

As discussed in Section 2.1.5, methods used to repair or replace concrete with surface defects include filling cracks, placing shotcrete on the surface, and adding or replacing mortar or concrete. Different types of mortar or concrete, such as conventional mortar or concrete, preplaced aggregate concrete, polymer-modified mortar or concrete, and epoxy mortar or concrete, can be used to repair defective surfaces. At the end of the 3R processes, the actor will prepare a 3R execution report that includes information about the actual 3R date, cost, etc. In addition, information about the treated surface defects can be archived in a way to allow relating this information to the future inspection data to track the element condition and reduce the potential cause of the defect by appropriate maintenance.

3.3.2. Product Modeling Concepts

The additional product-related concepts of OCSD cover the main concepts related to defects and repair product modeling, as explained below.

Defect Concepts

The defect is the final product of the inspection process. The diagnosis process examines the defect, and finally, if necessary, the 3R processes will focus on treating the defect. Since defects play a key role in all these processes, OCSD should cover the concepts of defects as the main product of these processes. Detailed semantic relationships are defined in OCSD to connect different types of concrete surface defects and their impact on defective elements. The OCSD concrete surface defects and the condition of the defective concrete surfaces main concepts and relationships are shown in Figure 6.

As discussed in Section 2.1.1, the attributes of defects are defined based on common types of concrete surface defects [17,18,136,137]. As shown in Figure 6, the defective product in OCSD covers information related to host and impacted elements, defect types, and condition of the defective concrete surfaces. The host element is the defective element. When there is a defect, the host element is usually weakened, which affects other elements, leading to the formation of new defects related to this process. As discussed in diagnosis concepts section, the actual cause of the defect will be determined in the process of cause analysis from the potential causes. Defects are defined by features such as generation period, orientation, location, dimensions, shape or patterns, and severity. Depending on the defect types, the changes in concrete surface forms include addition, deformation, section loss, and subtraction.

As discussed in Section 2.1.1, common types of surface cracks include: cracks, spalling, delamination, scaling, disintegration, erosion, honeycombing, etc. A functional defect is a defect that disrupts the expected performance of an element or structure. Issues caused by any, or a combination, of defects in the concrete surface can change the condition of the element, causing a functional defect of the element or structure.

As explained in Section 2.1.4, this section's definition of levels of severity and conditions of some specific concrete surface defects in OCSD are based on the Ontario Structure Inspection manual (OSIM) [18]. The value of severity of each defect based on Table 1 is added an individual's property set in OCSD. As discussed in Section 2.1.4, the severity of surface defects can be categorized as light, medium, severe, and very severe, and the condition of an element can be categorized into excellent, good, fair, and poor. In cracks, the severity can be divided into hairline, narrow, medium, and wide. The condition of the element depends on the severity of the defect.

The presence of some concrete surface defects indicates a specific condition in the element. For example, the presence of cold joints is a fair element condition. Moreover, some defects, such as stains, can have different conditions based on specific information. For example, some stains, such as those caused by biological growth and dust, do not indicate the weakness of the element, and the condition of the element can be assessed as good. However, some stains, such as stains caused by chemical reactions, water, and corrosion, indicate an abnormal condition in the element, and the condition of the element can be assessed as fair. Graffiti, bughole, and flatness defects only affect the appearance of the concrete and do not affect the strength of the concrete, so the condition of the defective element is considered good in the presence of these defects [17,18].

Repair Product Modeling Concepts

Repair product modeling should cover the following information: (1) host and impacted elements; and (2) a modified model of the element after the 3R process including changes in the geometry and materials.

4. Discussion

An example of an ontology evaluation using a case study is presented in another paper, which applies BIM and surface defect concepts using an ontology [121]. Ontology tools perform the consistency evaluation during the verification process [138–140]. In this regard, to evaluate the consistency and identify the subsumption relationships, HermiT OWL Reasoner [141], which is based on the hypertableau algorithm, is applied. A qualitative criteria-based evaluation method is used for evaluating the OCSD and demonstrating the benefits of the ontology. The qualitative criteria-based evaluation assesses the correctness and presentation of the main concepts and relationships of the developed ontology. This approach judges whether the ontology is clear and comprehensive and meets the objectives.

4.1. Consistency Evaluation Using Protégé

In Protégé, a description logic reasoner is used to perform the verification process and test the consistency criteria for OCSD [138,139]. OWL HermiT Reasoner explores the relationships and discovers the implicit relationships between classes. Furthermore, it verifies the concepts hierarchy and clarifies any inconsistencies in the ontology. For example, no individual can be at the same time an instance of two classes, which the reasoner can check. The HermiT OWL reasoner was utilized during the OCSD development stage and clarified some inconsistencies in the ontology. These results were utilized as feedback and input to rectify problems before going on to the final step.

4.2. Criteria-Based Evaluation

The semantic representation of OCSD was assessed through a survey with 11 questions, each focusing on different components of OCSD. The first question collected demographic and professional details about the respondents. The second question focused on the benefits of modeling information related to the inspection, diagnosis, and repair of concrete surface defects. The third and fourth questions examined the clarity and comprehensiveness of key inspection concepts and their relationships within OCSD. Similarly, the fifth and sixth questions addressed diagnostic concepts and relationships, while the seventh and eighth questions evaluated the clarity and comprehensiveness of the 3R principles and their relationships. The ninth and tenth questions explored defect-related concepts and relationships, and the final question assessed the potential of OCSD to enhance future BIM-based asset management systems. A summary of the survey questions is provided in Table 3.

Table 3. The evaluation questions of OCSD.

Q1	Name, organization/university, area of expertise, and years of experience.
Q2	Developing a unified ontology for modeling inspection, diagnosis, and repair related information of concrete surface defects will facilitate accessing and updating the information and streamlining the processes at different phases of the lifecycle resulting in improved efficiency and reduced rate of data input errors. Do you agree with this statement? ○ Strongly agree ○ Agree ○ Neither agree nor disagree ○ Disagree ○ Strongly disagree ○ No answer Comments: ………………………………………………………………………………………
Q3	Figure 3 represents the high-level concepts and relationships of the ontology for the inspection process of concrete surface defects. Do you find this representation clear and provide good understanding of the concepts in the domain? ○ Very clear ○ Clear ○ Somewhat clear ○ Not so clear ○ Not clear at all ○ No answer Comments: ………………………………………………………………………………………
Q4	Based on Figure 3, do you find the representation comprehensive? Comprehensiveness here means representing the main concepts and relationships for modeling the inspection-related information of concrete surface defects. ○ Very comprehensive ○ Comprehensive ○ Somewhat comprehensive ○ Not comprehensive ○ Missing lots of concepts ○ No answer Comments: ………………………………………………………………………………………
Q5	Figure 4 represents the high-level concepts and relationships of the ontology for the diagnosis process of concrete surface defects. The diagnosis process is based on processing the collected inspection data and the information about the surrounding conditions. Do you find this representation clear and provide good understanding of the concepts in the domain? ○ Very clear ○ Clear ○ Somewhat clear ○ Not so clear ○ Not clear at all ○ No answer Comments: ………………………………………………………………………………………
Q6	Based on Figure 4, do you find the representation comprehensive? Comprehensiveness here means representing the main concepts and relationships for modeling the diagnosis-related information of concrete surface defects. ○ Very comprehensive ○ Comprehensive ○ Somewhat comprehensive ○ Not comprehensive ○ Missing lots of concepts ○ No answer Comments: ………………………………………………………………………………………
Q7	Figure 5 below represents the high-level concepts and relationships of the ontology for the 3R (Repair, Rehabilitation, and Repair) processes of concrete surface defects. Do you find this representation clear and provide good understanding of the concepts in the domain? ○ Very clear ○ Clear ○ Somewhat clear ○ Not so clear ○ Not clear at all ○ No answer Comments: ………………………………………………………………………………………
Q8	Based on Figure 5, do you find the representation comprehensive? Comprehensiveness here means representing the main concepts and relationships for modeling the 3R-related information of concrete surface defects. ○ Very comprehensive ○ Comprehensive ○ Somewhat comprehensive ○ Not comprehensive ○ Missing lots of concepts ○ No answer Comments: ………………………………………………………………………………………
Q9	Figure 6 below represents the high-level concepts and relationships of the ontology for the defects and condition of the defective concrete surfaces. Do you find this representation clear and provide good understanding of the concepts in the domain? ○ Very clear ○ Clear ○ Somewhat clear ○ Not so clear ○ Not clear at all ○ No answer Comments: ………………………………………………………………………………………
Q10	Based on Figure 6, do you find the representation comprehensive? Comprehensiveness here means representing the main concepts and relationships for modeling concrete surface defects and condition of the defective surfaces. ○ Very comprehensive ○ Comprehensive ○ Somewhat comprehensive ○ Not comprehensive ○ Missing lots of concepts ○ No answer Comments: ………………………………………………………………………………………
Q11	OCSD provided knowledge is expected to influence the future BIM-based asset management systems and allow a new level of coordination and collaboration among the stakeholders of the project. Do you agree with this statement? ○ Strongly agree ○ Agree ○ Neither agree nor disagree ○ Disagree ○ Strongly disagree ○ No answer Comments: ………………………………………………………………………………………

The responses were collected using a five-point Likert scale to capture qualitative insights. Figures 3–6 were included in the survey to present details of OCSD. The questionnaire was distributed to 101 internationally recognized experts in BIM, concrete construction, inspection, diagnosis, and repair. A total of 29 experts participated in the survey, resulting in a response rate of 28.7%. Table 4 outlines the profiles of the participants, who collectively have 335 years of experience across relevant fields. The results of the survey answers are listed in Table 5.

Table 4. The respondents' profiles for the OCSD survey.

Number of Respondents	Areas of Expertise	Years of Experience (Total)
12	BIM, infrastructure management	165
7	Civil Engineering	87
4	Automation in construction	61
5	Information systems, ontology development	44
1	Architecture	22

Table 5. Distribution of the responses for the OCSD survey.

Q No	Ave.	SD	Results					
Q2	1.62	0.55	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer
			41.38%	55.17%	3.45%	0%	0%	0%
Q3	2.17	0.80	Very clear	Clear	Somewhat clear	Not so clear	Not clear at all	No answer
			17.24%	51.72%	20.69%	6.90%	0%	3.45%
Q4	1.92	0.53	Very comprehensive	Comprehensive	Somewhat comprehensive	Not comprehensive	Missing lots of concepts	No answer
			17.24%	65.52%	10.34%	0%	0%	6.90%
Q5	2.00	0.67	Very clear	Clear	Somewhat clear	Not so clear	Not clear at all	No answer
			17.24%	62.07%	10.34%	3.45%	0%	6.90%
Q6	1.92	0.53	Very comprehensive	Comprehensive	Somewhat comprehensive	Not comprehensive	Missing lots of concepts	No answer
			17.24%	65.52%	10.34%	0%	0%	6.90%
Q7	1.88	0.62	Very clear	Clear	Somewhat clear	Not so clear	Not clear at all	No answer
			24.14%	55.17%	13.79%	0%	0%	6.90%
Q8	1.92	0.46	Very comprehensive	Comprehensive	Somewhat comprehensive	Not comprehensive	Missing lots of concepts	No answer
			13.79%	75.86%	6.90%	0%	0%	3.45%
Q9	1.96	0.59	Very clear	Clear	Somewhat clear	Not so clear	Not clear at all	No answer
			17.24%	58.62%	13.79%	0%	0%	10.34%
Q10	2.04	0.59	Very comprehensive	Comprehensive	Somewhat comprehensive	Not comprehensive	Missing lots of concepts	No answer
			13.79%	58.62%	17.24%	0%	0%	10.34%
Q11	1.63	0.55	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer
			37.93%	51.72%	3.45%	0%	0%	6.90%

The responses to Q2 show that 41.38% of participants strongly agreed, 55.17% agreed, and 3.45% were neutral about the assertion that a unified ontology for modeling inspection, diagnosis, and repair-related information of concrete surface defects enhances information accessibility, updates, and process efficiency throughout different lifecycle phases. For Q3, the clarity of the main inspection concepts and relationships in OCSD was rated as very clear by 17.24% of respondents, clear by 51.72%, somewhat clear by 20.69%, and not so clear by 6.90%. Regarding Q4, which focuses on the comprehensiveness of inspection concepts and relationships, 17.24% of participants considered them very comprehensive, 65.52% rated them as comprehensive, and 10.34% found them somewhat comprehensive. The responses to Q5 indicate that the clarity of the diagnosis concepts and relationships in OCSD was rated very clear by 17.24%, clear by 62.07%, somewhat clear by 10.34%, and not so clear by 3.45%. For Q6, addressing the comprehensiveness of diagnosis concepts and relationships, 17.24% of respondents found them very comprehensive, 65.52% rated them comprehensive, and 10.34% considered them somewhat comprehensive. The ratings for Q7, focused on the clarity of the main 3R concepts and relationships in OCSD, show that 24.14% found them very clear, 55.17% rated them clear, and 13.79% somewhat clear. Responses to Q8, regarding the comprehensiveness of the 3R concepts and relationships, indicate that 13.79% rated them very comprehensive, 75.86% as comprehensive, and 6.90% as somewhat comprehensive. For Q9, the clarity of defect concepts and relationships in OCSD was rated very clear by 17.24%, clear by 58.62%, and somewhat clear by 13.79%. Q10, which pertains to the comprehensiveness of defect concepts and relationships, received ratings of very comprehensive (13.79%), comprehensive (58.62%), and somewhat comprehensive (17.24%). Finally, Q11, addressing the application of OCSD knowledge to future BIM-based asset management systems, showed that 37.93% of respondents strongly agreed, 51.72% agreed, and 3.45% were neutral.

These findings confirm that OCSD effectively covers the necessary concepts and relationships for inspection, diagnosis, and 3R processes related to concrete surface defects.

5. Conclusions

This paper developed an OCSD, an Ontology for Concrete Surface Defects, aimed at creating a unified knowledge framework that allows stakeholders to systematically access relevant information. OCSD comprises 335 classes, 51 relations, 27 attributes, and 31 individuals, encapsulating a comprehensive understanding of concepts and relationships related to concrete surface defects, as well as inspection, diagnosis, and the 3R processes. OCSD's consistency was validated using the HermiT OWL reasoner, ensuring alignment with all defined implicit relationships. A survey was conducted to assess OCSD's semantic representation, and the findings confirmed that it effectively encompasses the primary concepts and relationships of the domain, providing a clear understanding for domain experts. The evaluation demonstrates that OCSD successfully addresses all the competency questions defined in Section 3.1: (1) It was developed using a top-down approach, making it applicable to various types of structures and different lifecycle phases; (2) It offers comprehensive modeling of the generic aspects of inspection, diagnosis, and repair processes; (3) It reflects common aspects of OSIM guidelines at an abstract level, applicable to all types of concrete structures; (4) It contains key inspection-related concepts that can be used to extend the IFC standard; and (5) It accommodates new data collection technologies and associated inspection data.

The contribution of this paper lies in developing OCSD, an ontology for the inspection, diagnosis, and 3R processes of concrete surface defects. OCSD is expected to provide several benefits: (1) It can help future asset management systems by providing a comprehensive knowledge base that can be efficiently developed, modified, and processed. The knowledge model can serve as the foundation for re-engineering infrastructure management processes, facilitating analysis that reflects defects and repair changes in the structure, and supporting visual analytics to enhance diagnosis processes [142]; (2) By integrating all details of inspection, diagnosis, and 3R processes, it facilitates accessing and updating information, streamlining processes across different lifecycle phases, improving efficiency, and reducing data input errors; (3) It enables a new level of coordination and collaboration among project stakeholders, which is a key advantage of the Construction Information Modeling (CIM) approach; and (4) It can serve as a foundation for extending the IFC standard to include missing inspection-related information.

Despite these contributions, the research has some limitations that should be addressed in future work. First, the scope of this research does not cover all possible concepts of concrete surface inspection, diagnosis, and 3R processes. For instance, specialized types of inspection, such as underwater inspection, are not included in OCSD. Future extensions of OCSD should aim to cover these and other related concepts. Second, although OCSD is designed to complement BIM practices, it has not yet been fully integrated with existing BIM standards like the IFC. Future work should focus on mapping the concepts and relationships defined in OCSD to existing BIM schemas and standards. Additionally, future research could focus on integrating as-is, as-inspected, and as-repaired models into a digital twin to reflect surface defects within BIM or BrIM (Bridge Information Modeling). This integration would enhance the CIM approach by providing stakeholders with a dynamic platform to visualize and analyze the progression of defects over time, thereby improving collaboration and decision-making processes. By incorporating OCSD into a digital twin, the ontology's benefits could be extended to real-time applications, further strengthening asset management practices. Moreover, OCSD's knowledge base can be utilized to develop concrete surface inspection expert systems, software, or checklists, further enhancing its practical applicability in the field.

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