Benefits of decreasing the uncertainty in the current bridge inspection practice

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Abstract

Numerous bridges worldwide have surpassed their service-life. To ensure the user safety, visual inspections are commonly carried out with the consequent assignment of Defect Grades. On their basis, simplified risk evaluations and maintenance intervention prioritization are formulated. Per the inherent nature of visual inspections, these ones include two kinds of uncertainty: interpretation-related and representation-related one. If to attempt to reduce their influence in the inspective process, the former, being an intrinsic feature of inspections performed by humans, could not be tackled. The latter, instead, can be decreased on the basis of a novel semantics-based inspective methodology. On the grounds of a large set of real-life inspections outputs, the present article measures the inspection quality improvement following said uncertainty reduction. This was achieved through the Expected Utility Theory in terms of utility and costs. On the grounds of these two, a novel Uncertainty-induced Cost curve allows the assessment of the cost evolution as a function of the weight of the representation-related uncertainty. The proposed semantics-based inspective methodology represents an improvement over the current-day directly assigned condition grading one, thus improving the efficiency of structural reliability assessments. This leads to an improved prioritization of bridge maintenance interventions and to an increased user safety.

Keywords: Bridge, Bridge maintenance, Structural reliability assessment, Damage assessment, Inspection, Structural safety, Service Life, Bridge Inspection Quality.

1. Introduction

Civil engineering structures cover key roles in the proper functioning, security and comfort of any society. Thus, their time-induced deterioration and serviceability-jeopardizing issues – occurring throughout their service lifetime due to their constant use and environmental factors (e.g., corrosion, fatigue, creep and shrinkage-induced shortening and cracking) – should be treated with the equivalent criticality (Bado & Casas, 2021; Brighenti et al., 2022). Revealing data is provided by the American Society of Civil Engineers (ASCE)'s 2021 Infrastructure Report Card (ASCE, 2021). According to the latter, the U.S. has 617,000 bridges, 42% of which are 50 years old or more. Of the nation's bridges, 7.5% are structurally deficient and, on average, there are 178 million trips across a structurally deficient bridge each day. The most recent estimate puts the nation's backlog of bridge rehabilitation needs at USD 125 billion thus requiring a spending increase from USD 14.4 billion annually to USD 22.7 billion annually. Whilst this situation clearly changes from country to country, it is common to find large number of bridge stocks reaching the end of their service lifespans. For example, in Japan around 25% of bridges are at least 50 years and the number is expected to rise to 52% in 2029 (Ministry of Land Infrastructure Transport and Tourism of Japan, n.d.-b, n.d.-a). Furthermore, in Europe, the construction of highways started with an initial but limited experience in Italy in the 1920s and then with a massive one in Germany in the late 1930s (*Bast Bundesansalt Für Straßenwasen Brückenstatistik*, n.d.; Calvi et al., 2019). But it was only after the Second World War – mainly in the 1960s – that most European countries built the majority of the modern highway system (Calvi et al., 2019; Sobrino, 2007), largely in reinforced concrete (material to which corresponds a useful life of 50 years).

As observed by Regier and Hoult (Regier & Hoult, 2014), it is not feasible to replace all the structures that have surpassed their intended service lives because of the budget, logistical and environmental concerns that such widespread demolition and reconstruction process would bring along. The only other possible approach consists in keeping the assets that are still fit for purpose in service. Hence the importance of determining their deterioration level, serviceability performance and public safety through a series of inspections, monitoring and maintenance protocols (Bado et al., 2022). A programmed maintenance of structures implies the need to make the best use of the available economic resources with a focus on ensuring safety of its users (Chase et al., 2016). This is only possible by knowing the performance of the structures in terms of durability and defect evolution (Deng et al., 2014). This knowledge must be continuously updated with regularly in-situ observations and other key data on the asset conservation state, namely structural surveillance. Intervening on faulty structures well in advance can lead maximizing benefits with minimum financial commitment. In line with said idea, the inspections should be quick and easy to perform. Thus, they are generally performed in a visual manner from deck level, ground or water levels, or from permanent-access structures (Agrawal et al., 2021; Moore et al., 2001). Despite the recent surge of advanced methodologies for the assessment of structural health (Bado & Casas, 2021), visual inspections are still the most common structural surveillance technique.

In order to communicate the deterioration level of a bridge, a criterion for the evaluation of the gravity of each defect (relatively to the importance of the investigated element on the overall bridge static scheme) is required. As per (Iacovino et al., 2022), in many countries, such as Italy, Austria, Sweden, Canada and USA, a numeric scaling is adopted to represent the severity, extension and impact of the defect in question. Henceforth such a grade – expressing the structural gravity of a defect – will be referred to as Defect Grade.

The specific approach to Defect Grade assignment that the present article considers sees an inspector assigning said grade directly in-situ, without preliminary and electronic decision support (*SPEA Engineering. Manuale Della Sorveglianza SPEA*, 2015). The inspector simply observes a specific defect on the case study asset and notes down an associated Defect Grade on the inspection report. Henceforward, a Defect Grade assigned in such a manner will be referred to as an In-Situ Defect Grade (ISDG). Crucially, when proceeding with the above described inspective methodology, a systematic problem occurs. In particular, being such grade assigned strictly on the basis of an inspector's experience, technical ability and training, this one is automatically affected by uncertainty (Hsien-Ke et al., 2017). Furthermore, the lack of tools with which to reconstruct the reasoning of the inspector, renders the posterior interpretation of the ISDG quite challenging.

The concept of "inspective uncertainty" was exactly the topic of the authors' previous work (Poli et al., 2023), in which its main sources and aspects were analyzed. In particular, Poli et al. found that the inspective uncertainty was actually composed of two types of uncertainty: an (1) interpretation-related one and a (2) representation-related one. The former was found to arise from the intrinsic subjectivity of an inspector's thought/reasoning (different technical background, anchoring bias, prejudices, fast and frugal heuristics, etc.), the latter, instead, was found to arise from the intrinsic subjectivity of an inspector's way of conveying a thought, of articulating an engineering opinion and of communicating a verdict. Noteworthily, if one would want to reduce the overall uncertainty of the inspective process, only one of the two previously mentioned uncertainties could be tackled: the representation-related one. Indeed, as discussed in (Dorafshan & Maguire, 2018), the interpretation-related uncertainty is unavoidable as long as inspections are carried out by human inspectors (it is unthinkable to alter the way a person thinks and reasons). The representation-related uncertainty, instead, was found to have a much wider margin of intervention. In light of said margin, in (Poli et al., 2023) the authors developed a novel methodology aimed at decreasing the representation-related uncertainty in the inspective process. The main points of said novel methodology are reported in Section 2.

The present article reports the first application of said proposed methodology to the inspection of a real-life bridge stock (Section 3). In particular, inspectors assessing the state of the bridge stock with the proprietary ISDG methodology also performed the assessment with the novel methodology. The result were two comparable sets of Defect Grades taken from numerous bridges, components and defects. In the present article the authors will compare these two sets and quantify their divergence. In light of the nature of the two methodologies, such a comparison enables the quantification of the improvement in inspection quality facilitated by the reduction in representation-related uncertainty. To perform such quantification and determine the utility of this novel approach, the authors turn to a cornerstone approach for choice-taking under uncertainty: the Expected Utility Theory (Section 4). In particular, this popular approach in the economics field allows for a logically-consistent determination of the utility of different scenarios under conditions of uncertainty.

Through the application of the Expected Utility Theory, the divergence between the two methodologies will be quantified (both utility and monetary cost-wise), thus finally characterizing the influence of the representation-related uncertainty in the inspection process of a real-life bridge stock.

2. A novel Semantics-based inspective methodology: its key concepts

Whenever evaluating the structural reliability of infrastructure stocks and scheduling the respective maintenance interventions, it is of key importance reducing, to the greatest extent possible, any possible source of uncertainty in the inspective process. Indeed, the absence of a definite defect assessment practice is a significant concern for the correct operational management of infrastructural assets. It appears clear that a defect severity overestimation would cause infrastructure managers to allocate excessive resources to its maintenance. Crucially, this also removes resources from others potentially more critical defects. Oppositely, a defect severity underestimation could lead to a potential increase in deterioration and, possibly, to a structural failure. The presence of uncertainty in the inspective process might also lead to a wrong prioritization of maintenance operations which exposes both the users and the stakeholders of the infrastructures to unnecessary risks (Frangopol, 2019).

In their previous work (Poli et al., 2023), the authors studied the concept of "inspective uncertainty" and analyzed its main sources. In particular, Poli et al. found that the inspective uncertainty was actually composed of two types of uncertainty: an (1) interpretation-related one and a (2) representation-related one. The former arises whenever a technical interpretation of an observed damage slowly builds up in the inspector's mind (thus, unavoidable as long as inspections are carried out by humans). The latter, instead, occurs whenever the inspector conveys such interpretation into a synthetic and symbolic form i.e., the Defect Grade. The main aspects contributing to this uncertainty are: (1) unclear inspection objectives, (2) the absence of precise and unequivocal definitions of the inspective lexemes, (3) the absence of rules to combine the outputs of the several inspective aspects and, finally, (4) the impossibility to validate the accuracy of defect grades.

In light of such, the representation-related uncertainty was found to have a much wider margin of intervention. On a side note, this represents a major delimitation of the approach introduced in (Poli et al., 2023). Also, possible future developments might focus on the reduction of the interpretation-related uncertainty through a hybrid use of human/robotic inspections (Spencer Jr et al., 2019).

Moving back to the representation-related uncertainty, being the "representation" issue a problem of semantics-nature, one inevitably enters the semantic framework. This one is a linguistic subfield concerned with studying the meaning at various levels i.e., sentences, expressions or words. Indeed, in (Poli et al., 2023) it was inferred that only on the basis of a suitable semantic tool, it is possible to develop an inspective methodology with reduced uncertainty (in particular, the representation-related one). Hence, in-depth semantics literature reviews – bibliometric first and systematic after – were performed (Bayes, 1763; Casadei, 2003; Chomsky, 1959; Frege, 1892; Ogden & Richards, 1923; Saussure, 1916). On their basis it was found that (1) the true meaning of a concept (e.g., grade, defect) laid in the relationships between its linguistic components and (2) the semantic approach that best fitted the inspective field was Ogden and Richards' semantic triangle (Ogden & Richards, 1923). With the help of this one, by successfully bridging the semantic and inspective fields, the authors were able to construct an inspective process which performed well from, not only an engineering point of view, but also from the logical (Bayesian inference corroboration), semiotic and ontological perspective. In particular, through a mixed deduction-induction-abduction methodological process focused on the logical and semiotic aspects of the problematic at hand, in (Poli et al., 2023) the authors translated the inspection-semantics bridge into two functional and interconnected tools: a Defect Analysis Matrix and a Defect-Grading Algorithm.

Let us now see how these two tools tackled the representation-related uncertainty. In reference to the lack of clarity of the inspective objectives (first of the above mentioned issues behind the representation-related uncertainty), the authors delineated what they believe to be the key inspective objectives and inserted them in a matrix i.e., the Defect Analysis Matrix (see Table 1).

Table 1. Defect Analysis Matrix formalizing the inspection workflow through the definition of its key inspective objectives.

Defect code	**Inspection objectives**	**NO**	**1** Low	**2** Medium	**3** High

A	Urgency due to imminent safety hazard				
B	Capacity reduction				
C	Need for follow-up studies				
D	Defect evolution speed				
E	Defects generating disproportionate degradation				

As a matter of fact, according to the authors, these ones exhaustively described the influence of a defect on the bridge capacity and its user safety.

At this point, the authors want to draw a parallelism with COST Action TU 1406, Quality Control Specifications for Roadway Bridges – Standardization at an European Level (Campos e Matos et al., 2016; R. Hajdin, M. Kušar, S. Mašović, P. Linneberg, 2018; Strauss et al., 2016) where the European research community worked towards the goal of standardizing the definition of quality control plans for road bridges. In particular, said Quality Control Plan is intended to specify (1) all the activities and tools needed to ensure the bridge reliability, safety and serviceability performance aspects and (2) the extent/interval of inspections and the data necessary to estimate the Key [Structural] Performance Indicators with a large focus on forecasting their future developments (Kifokeris et al., 2018). One can easily see the alignment between the scopes of TU1406 and of the methodology introduced in the present article. The above mentioned focus on forecasting the future development of damage processes and, consequently, of the Key Performance Indicators, is embodied by Objective Codes D and E. Meanwhile, Objective Code B reflects TU1406's defect classification according to their occurrence in vulnerable areas of the structure i.e., causing capacity reductions. Indeed, as in (Poli et al., 2023), the evaluation of objective codes should be evaluated on singular structural elements but, importantly, in the context of their role in the overall static system of the bridge i.e., taking into account vulnerable/critical structural elements. Noteworthily, these evaluations can be achieved only on the grounds of a comprehensive and methodical study of the bridge design documents. Finally, TU1406's WG3 report (R. Hajdin, M. Kušar, S. Mašović, P. Linneberg, 2018) observes that whenever a damage process is gradual and observable (e.g. corrosion related to structural steel), a proper inspection strategy can be employed. A different one would be required if the damage process is non-observable (e.g. corrosion of post-tensioning steel). A clear parallelism with Objective Code C can be noticed.

TU1406 correctly observes in its WG3 report that "whenever a damage process is in progress and observable, it will be manifested by consequences visible by inspectors and recorded as observations. […] Generally, the observation is a perception of human senses". Then again, the report does not delve deeper in the subject and all manner of discussion on uncertainty is relegated to the structural reliability model of WG3 Section 6.4. Indeed, here the uncertainty value quantifies the uncertainty behind the magnitude of the resistance reduction caused by the observed damage, completely uncorrelated with the defect interpretation and representation-related uncertainties. The model presented in (Poli et al., 2023), instead, not only considers these two uncertainties but provides a methodology to decrease them. Indeed, when one deals with "representation" issues, one also automatically deals with the field of semantics on the basis of which the novel model was developed. The reader should keep in mind that this methodology is not intended to substitute the uncertainty calculated in the structural reliability method (these two are distinct), but is rather aimed at improving the results of the structural reliability evaluation by inputting in this one less uncertain damage evaluations. The combination of the two above methodologies is the topic of future publications from the authors' part.

Let us now move on to the other main problematic at the basis of the representation-related uncertainty i.e., the absence of precise and unequivocal definitions of the inspective lexemes. To counteract this, accurate and unequivocal definitions of these was performed by: (1) providing detailed definitions of inspective lexemes (A-E in the Defect Analysis Matrix), (2) quantifying them and (3) restricting the possible assessments to (No, 1, 2, 3) (see Table 2).

Table 2. Definition of the main inspective lexemes of the Defect Analysis Matrix.

Objective code	NO	1	2	3
A	No imminent safety hazard at the time of the inspection			Imminent safety hazard at the inspection time
B	Lack or neglectability of reduction in the	Reduction in the carrying capacity of the bridge ≤ 5%	Failure of a singular structural element causing a local collapse; reduction	Failure of a structural element that could potentially lead to a global bridge collapse; reduction

	carrying capacity of the bridge		in the carrying capacity of the bridge of 5-20%	in the carrying capacity of the bridge ≥ 20%
C	Follow-up studies are not required			Follow-up studies are required
D	No risk of defect degeneration	Risk of defect degeneration in the medium-long term (2-3 years)	Risk of defect degeneration in about 1-2 years	Risk of defect degeneration before the next routine inspection
E	No potential for deterioration	Water infiltration with no risk of degradation of structural elements underneath	Water infiltration with risk of degradation of structural elements underneath	Similar to E=2, with the addition of critical structural element underneath whose degradation could compromise the globality of the structure

To be kept in mind, the methodology introduced in (Poli et al., 2023) is not exclusive for structural elements, but also for equipment components. For a more accurate and detailed discussion of the content of Table 2 and of the included inspective objectives, please refer to (Poli et al., 2023).

The Defect Analysis Matrix of Table 2 additionally tackles the other main issue of the representation-related uncertainty i.e., the impossibility of validating the correctness a defect grade. Clearly, through said matrix an infrastructure manager can, at any time, trace back key information on the damage and verify the correctness of its evaluation. Finally, the last issue issue of the representation-related uncertainty i.e., the lack of combination rules of different inspective aspects (content of the Defect Analysis Matrix), was tackled with a chief unambiguous tool: the computer. By means of computational ontology (that science that regulates the communication with computers and models the structure of a system, organizing and relating its components (Guarino et al., 2009)), the authors were able to formalize a set of combination rules through a semiautomatic approach i.e., a Defect-Grading Algorithm (Figure 1).

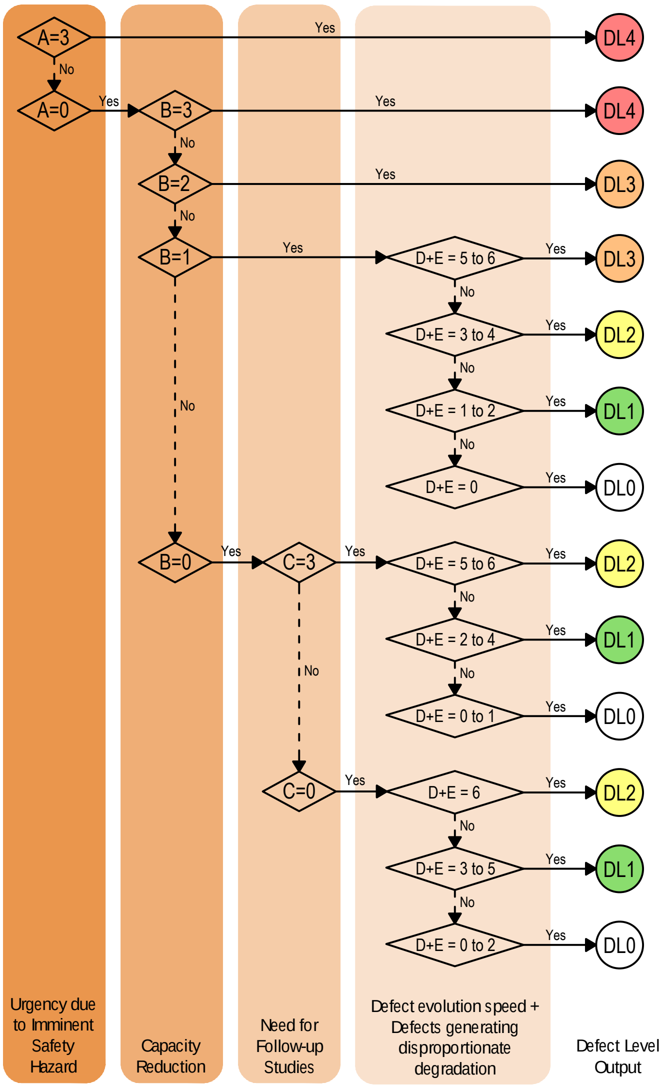


Figure 1. Flow chart designed to extract a single defectology grade (which will later be named Semantics-based Grade) on the grounds of data present in the Defect Analysis Matrix.

The outputs of the algorithm were expressed on a scale from DL0 to DL4, with DL standing for "Defect Level". Each DL was defined as follows:

- DL0: Defects requiring interventions in the long term;
- DL1: Defects requiring interventions in the medium-long term (5-10 years);
- DL2: Defects requiring interventions in the medium-short term (2-5 years);
- DL3: Defects with a minor effect on the bridge structural capacity (not significantly compromising safety factors). These ones requiring interventions in the short term (< 2 years);
- DL4: Defects leading to a reduction of the structural safety coefficients. These ones requiring immediate interventions.

The Defect-Grading Algorithm is characterized by a structure of hierarchical type according to the user safety level. It converts the output of the inspective objectives of the Defect Analysis Matrix into a singular Defect Grade i.e., Semantics-based Grade or simply Semantic Grade (SG). This grade is significantly depurated from representation-related uncertainty as it is created on unequivocal and mathematical basis and not on the personal paradigms of each inspector. In summary, the present section briefly recapped the work presented in (Poli et al., 2023) which defined a semantics-based inspective methodology aimed at decreasing the representation-related uncertainty (thus improving the process of prioritization of bridge maintenance interventions and the user safety) by means of:

(1) Clear inspective objectives through the introduction of the Defect Analysis Matrix;
(2) Inspective lexemes through the detailing and quantification of each key inspective aspects of the Defect Analysis Matrix;
(3) A set of combination rules of the key inspective aspects through the introduction of the Defect-Grading Algorithm and the extrapolation of a singular Semantics-based Grade;
(4) A validation process to ascertain the correctness of a defect grade.

In the following sections, the above introduced semantics-based inspective methodology represents the basis of a novel research work i.e., the quantification of the inspection quality improvement following said uncertainty reduction.

3. Applying the novel Semantics-based Inspective Method to a real-life bridge stock

In the previous sections it was discussed how, in the context of visual inspections for the structural condition assessment of a bridge, the ISDG practice often sees the assignment of Defect Grades directly in-situ without pre-established decision support which, in turn, might entail a non-neglectable amount of uncertainty. The present section will now report the first application of the Semantics-based Inspective Methodology (discussed in Section 2) to the inspection of a real-life bridge stock. On the grounds of this one, the authors will compare the output of such novel methodology and the ISDG and quantify their divergence.

The real-life case study bridge stock on which the inspections were performed was composed of 46 bridges located in northern Italy and managed by the biggest Italian infrastructure manager. On each of these 46 bridges, the same inspectors assessing the state of the bridge stock with the proprietary ISDG methodology (in the context of a 2020 routine annual inspection) also performed the assessment with the novel semantics-based methodology. The result, two comparable sets of Defect Grades per each bridge. Furthermore, the inspectors were not in possession of the Defect-Grading Algorithm, therefore she/he was unable to verify whether her/his ISDG matched with the final SG (the output of the semantic method). As such, any divergence between the two grades is strictly a representation-related issue and not an interpretation-related one. In other words, the ISDG/SG divergence represents the weight of the representation-related uncertainty on the ISDG.

Figure 2 details the outputs of the inspections and, in particular, it lists the (i) bridge name, (ii) defect location, (iii) ISDG, (iv) evaluation A-E of the Defect Analysis Matrix for each defect and (v) SG obtained through the application of the Defect-Grading Algorithm. Note that, being the example a real-life case study, further sensible data cannot be disclosed as a matter of professional confidentiality. Furthermore, the authors were unable to verify the correctness of the evaluations as they were provided only with the inspection reports (containing a single picture of the defect, intended to merely represent the defect and not exhaustively describe it). In Figure 2, the same DL color code is used as the one in Figure 1 i.e., according to the level of severity of the reported defect. Note that, in the case study set of inspections, no DL4 were assigned. Indeed, this grade is seldom assigned as it is only used for those rare situations in which grievous defects with structural safety coefficient reductions are present.

NAME	Defect Location	ISDG	A	B	C	D	E	SG
Bridge Nr. 1	Piers-Pier caps	DL1	0	0	0	2	1	DL1
Bridge Nr. 1	Deck-Cross beams	DL0	0	0	0	2	0	DL0
Bridge Nr. 1	Supports-Support rod	DL1	0	1	0	2	1	DL2
Bridge Nr. 1	Supports-Support rod	DL1	0	1	0	2	1	DL2
Bridge Nr. 2	Deck-Beams	DL1	0	0	0	1	1	DL0
Bridge Nr. 3	Deck-Beams	DL1	0	0	0	1	1	DL0
Bridge Nr. 3	Deck-Overhangs	DL2	0	1	0	1	1	DL1
Bridge Nr. 4	Piers-Pier caps	DL1	0	0	0	2	1	DL1
Bridge Nr. 4	Water disposal	DL1	0	0	0	1	3	DL1
Bridge Nr. 5	Deck-Beams	DL0	0	1	3	1	0	DL1
Bridge Nr. 6	Water disposal	DL0	0	0	0	2	3	DL1
Bridge Nr. 6	Supports-Appliances	DL0	0	0	0	2	0	DL0
Bridge Nr. 7	Deck-Beams	DL1	0	1	0	2	1	DL2
Bridge Nr. 7	Deck-Beams	DL0	0	0	0	1	0	DL0
Bridge Nr. 7	Deck-Cross beams	DL1	0	0	0	2	0	DL0
Bridge Nr. 7	Deck-Overhangs	DL0	0	1	0	2	0	DL1
Bridge Nr. 7	Supports-Support rod	DL1	0	1	0	2	0	DL1
Bridge Nr. 7	Supports-Support rod	DL1	0	0	0	2	0	DL0
Bridge Nr. 8	Foundations	DL0	0	1	3	2	1	DL2
Bridge Nr. 8	Seismic shock absorbers	DL1	0	0	3	0	0	DL0
Bridge Nr. 9	Foundations	DL0	0	1	3	2	1	DL2
Bridge Nr. 9	Supports-Appliances	DL0	0	0	0	2	0	DL0
Bridge Nr. 10	Piers-Pier caps	DL0	0	0	0	1	0	DL0
Bridge Nr. 10	Deck-Beams	DL0	0	0	0	3	0	DL1
Bridge Nr. 10	Supports-Appliances	DL0	0	0	3	1	0	DL0
Bridge Nr. 11	Deck-Box girders	DL1	0	0	0	2	0	DL0
Bridge Nr. 12	Piers-Elevations	DL0	0	1	0	2	0	DL1
Bridge Nr. 12	Deck-Cross beams	DL0	0	1	0	2	1	DL2
Bridge Nr. 13	Abutments	DL0	0	1	0	2	0	DL1
Bridge Nr. 13	Deck-Box girders	DL0	0	1	0	2	0	DL1
Bridge Nr. 13	Water disposal	DL0	0	0	0	2	3	DL1
Bridge Nr. 14	Deck-Box girders	DL1	0	0	0	1	1	DL0
Bridge Nr. 14	Deck-Box girders	DL1	0	0	0	2	1	DL1
Bridge Nr. 14	Deck-Box girders	DL1	0	0	0	1	1	DL0
Bridge Nr. 14	Deck- Box girders	DL1	0	0	3	2	2	DL1
Bridge Nr. 15	Deck-Box girders	DL1	0	0	3	2	2	DL1
Bridge Nr. 16	Deck-Box girders	DL0	0	1	3	1	3	DL2
Bridge Nr. 17	Deck-Box girders	DL0	0	0	0	2	2	DL1
Bridge Nr. 17	Water disposal	DL0	0	0	0	1	3	DL1
Bridge Nr. 18	Abutments	DL0	0	0	0	2	0	DL0
Bridge Nr. 18	Water disposal	DL0	0	0	0	1	3	DL1
Bridge Nr. 19	Abutments	DL1	0	0	0	2	1	DL1
Bridge Nr. 19	Deck-Cross beams	DL0	0	0	0	2	0	DL0
Bridge Nr. 19	Seismic shock absorbers	DL1	0	0	3	2	0	DL1
Bridge Nr. 19	Inside-Box girders	DL1	0	0	3	2	1	DL1
Bridge Nr. 20	Water disposal	DL1	0	0	0	1	3	DL1
Bridge Nr. 21	Abutments	DL1	0	0	0	2	0	DL0
Bridge Nr. 21	Deck-Box girders	DL1	0	0	0	2	2	DL1
Bridge Nr. 21	Deck-Box girders	DL1	0	0	0	2	2	DL1
Bridge Nr. 21	Water disposal	DL1	0	0	0	1	3	DL1
Bridge Nr. 21	Water disposal	DL1	0	0	0	1	3	DL1
Bridge Nr. 22	Water disposal	DL1	0	0	0	1	3	DL1
Bridge Nr. 23	Abutments	DL1	0	1	0	2	0	DL1
Bridge Nr. 24	Deck-Beams	DL2	0	1	0	2	1	DL2
Bridge Nr. 24	Deck-Beams	DL2	0	1	0	2	1	DL2
Bridge Nr. 25	Deck-Beams	DL1	0	1	3	2	1	DL2
Bridge Nr. 25	Deck-Overhangs	DL0	0	0	0	2	1	DL1
Bridge Nr. 26	Abutments	DL1	0	0	0	2	1	DL1
Bridge Nr. 26	Abutments	DL1	0	0	0	2	1	DL1
Bridge Nr. 26	Deck-Overhangs	DL1	0	0	0	1	3	DL1
Bridge Nr. 26	Water disposal	DL1	0	0	0	1	3	DL1
Bridge Nr. 27	Abutments	DL1	0	0	0	2	1	DL1
Bridge Nr. 27	Deck-Box girders	DL1	0	0	3	2	1	DL1
Bridge Nr. 27	Water disposal	DL1	0	0	0	2	3	DL1
Bridge Nr. 27	Supports-Appliances	DL0	0	0	0	2	0	DL0
Bridge Nr. 28	Deck-Box girders	DL0	0	0	0	2	1	DL1
Bridge Nr. 29	Piers-Elevations	DL0	0	1	3	2	0	DL1
Bridge Nr. 29	Piers-Elevations	DL0	0	1	3	2	0	DL1
Bridge Nr. 29	Deck-solette	DL0	0	1	3	2	0	DL1
Bridge Nr. 30	Piers-Pier caps	DL0	0	1	3	2	1	DL2
Bridge Nr. 30	Supports-Appliances	DL1	0	0	0	1	1	DL0
Bridge Nr. 31	Piers-Pier caps	DL0	0	1	0	2	0	DL1
Bridge Nr. 31	Water disposal	DL0	0	0	0	2	2	DL1
Bridge Nr. 32	Foundations	DL0	0	0	0	2	0	DL0
Bridge Nr. 32	Abutments	DL1	0	0	0	2	0	DL0
Bridge Nr. 32	Deck-Box girders	DL0	0	0	0	1	0	DL0
Bridge Nr. 32	Water disposal	DL1	0	0	0	0	2	DL0
Bridge Nr. 32	Seismic shock absorbers	DL1	0	0	3	1	0	DL0
Bridge Nr. 33	Abutments	DL0	0	0	0	2	0	DL0
Bridge Nr. 33	Supports-Appliances	DL1	0	0	0	1	0	DL0
Bridge Nr. 34	Water disposal	DL1	0	0	0	2	3	DL1
Bridge Nr. 34	Water disposal	DL1	0	0	0	2	3	DL1
Bridge Nr. 34	Seismic shock absorbers	DL1	0	1	0	2	0	DL1
Bridge Nr. 35	Deck-Cross beams	DL1	0	1	3	1	0	DL1
Bridge Nr. 35	Deck-Box girders	DL1	0	1	3	1	0	DL1
Bridge Nr. 35	Water disposal	DL1	0	0	0	2	3	DL1
Bridge Nr. 35	Water disposal	DL1	0	0	0	2	3	DL1
Bridge Nr. 36	Deck-Box girders	DL2	0	1	0	2	1	DL2
Bridge Nr. 36	Deck-Box girders	DL0	0	1	0	2	0	DL1
Bridge Nr. 36	Deck-Box girders	DL1	0	1	0	2	0	DL1
Bridge Nr. 36	Seismic shock absorbers	DL1	0	1	3	2	0	DL1
Bridge Nr. 37	Deck-Box girders	DL2	0	1	3	2	1	DL2
Bridge Nr. 37	Seismic shock absorbers	DL0	0	1	3	2	0	DL1
Bridge Nr. 38	Abutments	DL0	0	0	0	2	0	DL0
Bridge Nr. 38	Abutments	DL1	0	0	0	3	0	DL1
Bridge Nr. 38	Deck-Overhangs	DL0	0	1	0	2	1	DL2
Bridge Nr. 38	Supports-Appliances	DL1	0	0	0	2	1	DL1
Bridge Nr. 39	Deck-Beams	DL3	0	1	0	2	0	DL1
Bridge Nr. 40	Deck-Beams	DL3	0	2	3	2	1	DL3
Bridge Nr. 41	Deck-Beams	DL3	0	1	0	2	0	DL1
Bridge Nr. 42	Deck-Beams	DL3	0	1	0	2	0	DL1
Bridge Nr. 43	Abutments	DL1	0	0	3	1	0	DL0
Bridge Nr. 43	Deck-Overhangs	DL1	0	0	0	1	0	DL0
Bridge Nr. 43	Supports-Support rod	DL1	0	0	3	1	0	DL0
Bridge Nr. 44	Deck-Beams	DL1	0	0	0	2	0	DL0
Bridge Nr. 44	Deck-Overhangs	DL0	0	0	0	1	0	DL0
Bridge Nr. 44	Deck-Overhangs	DL0	0	0	0	1	0	DL0
Bridge Nr. 44	Deck-Box girders	DL1	0	0	3	1	0	DL0
Bridge Nr. 45	Deck-Box girders	DL0	0	0	0	2	2	DL1
Bridge Nr. 46	Supports-Appliances	DL1	0	0	0	1	2	DL1
Bridge Nr. 46	Deck-Box girders	DL0	0	0	3	1	2	DL1
Bridge Nr. 46	Deck-Box girders	DL0	0	0	3	1	2	DL1

Figure 2. Case study bridges with lists of their defects reporting: the bridge name, the defect location, the ISDG collected downstream the 2020 annual inspection, the defect analysis matrix evaluations (A-E) and the SG.

An optimal tool to display the ISDG/SG divergence of Figure 2 is through a Multi-Class Classification Confusion Matrix (henceforth simply referred to as Confusion Matrix). In the field of statistical classification, a Confusion Matrix, also known as error matrix, represents the instances in an actual class (the columns) and in a predictive class (the rows) – or vice versa – match or not, allowing to assess whether the system is "confusing" or mislabeling the two classes. In our case, this matrix provides information on how far a value s (ISDG) is from a predicted value $\tilde{s}$ (SG). In other words, the matrix counts how many times the ISDG is equal to the SG, how many times it is not and how far the two values are. In Table 3, the Confusion Matrix has been created on the grounds of the data of Figure 2.

Table 3. Confusion Matrix with columns representing the SG and rows representing the ISDG.

ISDG	DL0	15	23	6	0	0
	DL1	19	36	4	0	0
	DL2	0	1	4	0	0
	DL3	0	3	0	1	0
	DL4	0	0	0	0	0
		DL0	DL1	DL2	DL3	DL4
		SG				

The 5x5 matrix includes a total of 112 defects distributed in its cells. Whenever a value is on the main diagonal, it means that ISDG perfectly matches the SG. Instead, as the cells move away from the main diagonal, it is suggested that a gradually greater divergence exists. A color code is used in the matrix to give an idea of the extent of the divergence in terms of user safety. In particular, (i) green indicates the perfect match; (ii) white is used whenever the uncertainty leads to an overestimation of a defect, thus suggesting an unnecessary maintenance intervention (still in favor of safety); (iii) the other colors indicate the number of classes by which the gradings diverge and the decrease of user safety (yellow – 1, orange – 2, red – 3, dark red – 4). The most dangerous situation is represented by the dark red color suggesting that the impact of the representation-related uncertainty leads to a grave mislabeling and the failed diagnosis of the need for immediate evacuation. To clarify how Table 3 was built, let us consider the top left cell. This one reports how many defects listed in Figure 2 have an ISDG = DL0 and an SG = 0. As visible in Figure 2, this situation can be spotted for 15 different defects, thus the top left cell of Table 3 reports 15. Moreover, as can be observed in the table, the inspector correctly evaluated 56 defects (ISDG=SG), was off 1 class in 47 and of 2 classes in 9. Of the latter, only 6 (in orange) represent a substantial risk for user safety.

In order to find any relationship between our two random variables (ISDG and SG), the authors now study their joint distribution (Jaynes, 1990). In probability theory, the Joint Probability is a statistical measure that calculates the likelihood of two events occurring together. In other words, it is the probability of event Y occurring at the same time as event X, hence P(X∩Y). Said probability is quantified as a number between 0 and 1 inclusive, where 0 indicates an impossible chance of occurrence and 1 denotes the certain outcome of an event. In the following, the authors report the Joint Probability Matrix for the case study as visible in Table 4.

Table 4. Joint Probability Matrix given the case study data.

ISDG	DL0	0.134	0.205	0.054	0	0
	DL1	0.170	0.321	0.036	0	0
	DL2	0	0.009	0.036	0	0
	DL3	0	0.027	0	0.009	0
	DL4	0	0	0	0	0
		DL0	DL1	DL2	DL3	DL4
		SG				

Table 4 provides crucial information on the extent of the ISDG/SG divergence, such as:

- ISDG=SG in 50% of the cases (cumulative values on the main diagonal);
- As a consequent of the previous point, it can be stated that the representation-related uncertainty affected the assignment of the Defect Grade in 50% of the cases (with different degrees);
- For SG=DL1 the cumulative divergence is equal to 56.2%, suggesting how easy it is for inspectors to confuse DL1 with DL0 and DL2 (low magnitude defects) for direct assignments of Defect Grades;
- The maximum divergence arises for SG=DL1 and ISDG=DL0 scenario and is equal to 20.5% (1-class divergence);
- In 50.1% of the cases a 1-class divergence exists, a 2-classes divergence exists in 8.1% of the cases and finally no 3-classes divergence or higher exists, demonstrating that such high magnitude mislabeling errors are rarely committed.

Finally, following a comparison between the outputs of the Semantics-based Inspective Methodology and the directly assigned condition grading one, a non-neglectable divergence between them is disclosed. In the next section, the authors will proceed to assess the extent of the inspection quality improvement in light of the uncertainty reduction, by quantifying said benefit.

4. Expected Utility Theory to assess the weight of uncertainty on the case study inspection set

With the aim of quantifying the improvement in the inspection quality achieved through the implementation of the Semantics-based Methodology versus the current-day one (hence, assessing how heavily does the representation-related uncertainty influence a Defect Grade), the authors took inspiration from the well-known approach to decision making in this context of uncertainty i.e., the Expected Utility Theory. Generally, the theory measures the "worth" of an outcome but, in our case, it is adopted to assess the weight of the representation-related uncertainty in the inspective process. A major advantage behind the use of this theory, is the possibility of quantifying said improvement into a single cumulative value.

4.1 A brief excursus on the Expected Utility Theory

Traditionally, utility functions are defined for stochastic problems that involve uncertainty. The utility or value functions may be thought of as evaluative mechanisms that can be used to measure the value of a particular solution (Ramanathan, 2004). To understand how the Expected Utility Theory works one should know that it is intended to formally define how rational decisions are made. A decision consists in the task of choosing an action a from a set of possible actions A. The decision is based on the knowledge of one or several discrete state variables x, described by a function named Mass Function $X \sim p(x)$. The Utility $\mathbb{U}(a,x)$ quantifies the relative preferences for the joint result of taking an action a while being in a state x (Goulet, 2020). In an uncertain context, the perceived benefit of an action a_i is measured by the Expected Utility, $\overline{\mathbb{U}}(a) \equiv \mathbb{E}[\mathbb{U}(a,x)]$. When X is a discrete random variable so that $x \in X$, the Expected Utility is as in Equation (1).

$$\mathbb{E}[\mathbb{U}(a,x)] = \sum_{x \in X} \mathbb{U}(a,x) \cdot p(x) \tag{1}$$

If to apply the above explained theory to the current bridge inspection case study, one does not measure the value of a particular solution, but rather the negative impact of the ISDG/SG divergence. To quantify it, the Utility Matrix $\mathbb{U}(a,x)$ – usually employed to calculate profits – can be substituted with a matrix that expresses losses, namely a Penalty Matrix $\mathbb{Z}(a,x)$. This one can represent any kind of losses such as costs, fatalities, probability of an accident, etc. The Utility Matrix and the Penalty Matrix are equal but opposite ($\mathbb{Z}(a,x) = -\mathbb{U}(a,x)$), hence the Penalty Matrix could also be understood as a Dis-Utility Matrix. Furthermore, for the present case study, a, x are substituted by s and $\tilde{s}$ (respectively, ISDG and SG) and the Mass Function $p(x)$ is substituted by the Joint Probability Matrix $P(s,\tilde{s})$. Now, by replacing them in Equation (1), Equation (2) can be extracted.

$$\mathbb{E}[\mathbb{U}(s,\tilde{s})] = \sum_{i=1}^{n} \sum_{j=1}^{m} -\mathbb{Z}(\tilde{s}_i, s_j) \cdot P(s_i, \tilde{s}_j) \tag{2}$$

Figure 3 displays how to combine the components of Equation (2) – the Penalty and the Joint Probability Matrices – and the output of the Defect Analysis Matrix (through the Defect-Grading Algorithm) to obtain a complete flow chart for the extraction of a single utility value for a set of inspections.

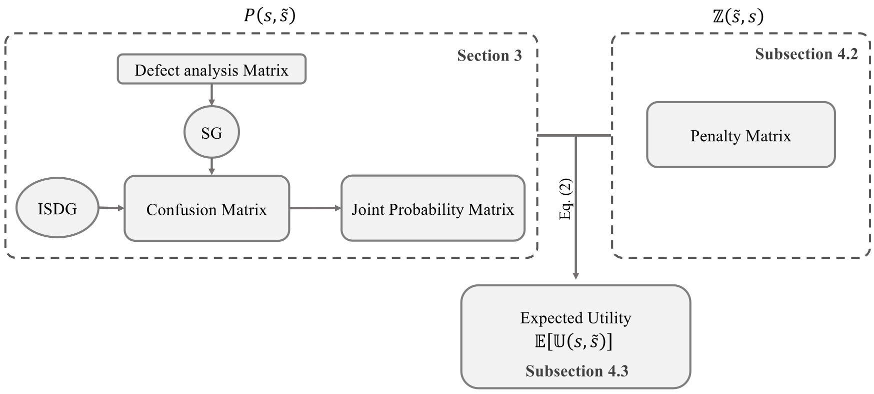


Figure 3. Algorithmic flow chart for the extraction of an expected utility value.

As visible in Figure 3, the Joint Probability Matrix $P(s,\tilde{s})$ is combined with the Penalty Matrix $\mathbb{Z}(s,\tilde{s})$ to assess the Expected Utility $\mathbb{E}[\mathbb{U}(s,\tilde{s})]$ by means of Equation (2). Once again, the extracted Expected Utility value embodies the benefit of integrating the Semantics-based Methodology in the structural condition assessment of a bridge. In the following subsection, different types of Penalty Matrices will be discussed, including the steps on how to obtain them. In such a way, having already obtained the Joint Probability Matrix in Section 3 and introducing the Penalty Matrix in Subsection 4.2, the authors will finally have all the tools necessary for the calculation of the Expected Utility (Subsection 4.3).

4.2 Utility and Costs: Different Penalty Matrices

Per the above Expected Utility Theory, a singular value of benefit can be expressed in a variety of forms, such as utility, gravity, money, losses, etc. according to the desired output. No matter the chosen form, the value still embodies the weight of the representation-related uncertainty in a Defect Grade. In the present article, the authors convey the benefits through two different parameters – utility and costs –, consequently using two different penalty matrices.

The simpler Penalty Matrix, the one in terms of utility, is built assigning a dis-utility in terms of gravity to each ISDG/SG divergence (the Dis-Utility Matrix was discussed in Subsection 4.1). In such a way, a good measure of the ISDG/SG correlation (and of the influence of the representation-related uncertainty) is provided. To structure it, the authors opted for Pearson's Index of Correlation (Benesty et al., 2009) (quadratic in nature) and a matrix dimension compatible with the one of the Joint Probability Matrix i.e., a 5x5 matrix. Despite a different correlation could be employed (e.g. linear correlation), a quadratic one was adopted to express how increasingly grievous the ISDG-SG divergence is. The obtained matrix, illustrated in Table 5, entails a quadratic correlation between the Defect Grades and their divergence.

Table 5. Penalty Matrix defined according to Pearson’s Index of Correlation.

ISDG	DL0	0	1	4	9	16
	DL1	1	0	1	4	9
	DL2	4	1	0	1	4
	DL3	9	4	1	0	1
	DL4	16	9	4	1	0
		DL0	DL1	DL2	DL3	DL4
		SG				

For example, to a 3-classes mislabeling error/divergence, a penalty of 9 is assigned, whilst a 16 one is assigned to a 4-classes divergence. Now, similarly, a Penalty Matrix in terms of costs can also be built associating in each cell an economic loss to various ISDG/SG divergences. Note that, this one embodies merely a symbolic meaning of cost which does not include potential costs connected to reparation interventions and implementation (training of the inspectors and the development of a supporting informatic infrastructure). This economic value is representative solely of the benefits that one could gain by reducing the uncertainty in the inspective process (achieved through the application of the novel Semantics-based Methodology). This Penalty Matrix, similarly to the Joint Probability Matrix, has to be a 5x5 one and focuses on the two main aspects behind bridge upkeeping: the safeguard of human lives and the costs of maintenance interventions. The so delineated Penalty Matrix is structured as in Table 6.

Table 6. Structure of the Penalty Matrix in terms of costs.

ISDG	DL0	0	I1	I2	I3	I4
	DL1	M1	0	I1	I2	I4
	DL2	M2	M2	0	I1	I4
	DL3	M3	M3	M3	0	I4
	DL4	M4	M4	M4	M4	0
		DL0	DL1	DL2	DL3	DL4
		SG				

In Table 6, I_i represent the user injury/damage costs, whilst M_i the bridge maintenance/reconstruction ones. On the diagonal no penalty is assigned (=0) as no ISDG/SG divergence exists (hence, no costs induced by uncertainty-related errors). The upper-right side of the matrix (area marked in red) encompasses those uncertainty-induced mislabeling errors per which the defects are underestimated, i.e. the need for risk-reducing maintenance interventions is ignored, putting human lives at risk. Note that the red area was filled in with a diagonal distribution of costs I1, I2 and I3 corresponding respectively to a mislabeling error of 1 class, 2 or 3. This, except for the DL4 SG column – presence of a grievous defect with a safety coefficient reduction – which was filled with a single I4 cost corresponding to the Statistical Value of human Life VSL (discussed later on).

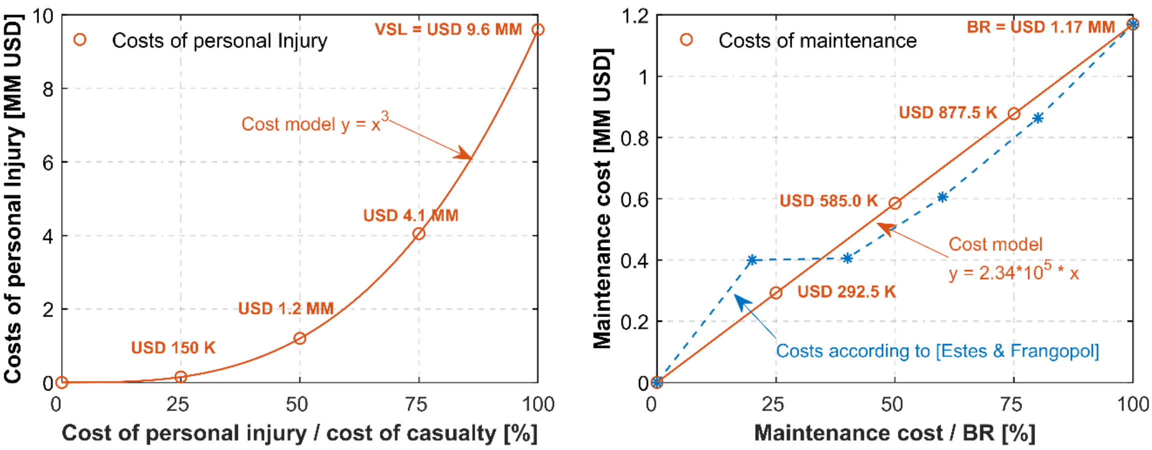
Instead, the lower-left side of the matrix (area in blue) encompasses those uncertainty-induced mislabeling errors per which the gravity of the defects is overestimated, thus creating a large margin of safety for human lives. In this case, as a result of the mislabeling, unnecessary maintenance interventions are prompted, resulting in unnecessary intervention costs. Considering that each ISDG leads to a single maintenance intervention – with a specific cost –, the authors filled in the rows of the matrix with a constant cost distribution.

In order to determine the I_i and M_i costs, it was necessary to research the VSL and the costs of bridge maintenance/reconstruction. Starting from the former, there is no standard concept for the value of human life in economics. However, when looking at risk/reward trade-offs that people make with regard to their health, economists often consider the VSL. This one is an estimate of the willingness to pay for a reduction in mortality risks (Gruber, 2011) (not the actual value of life). VSL is an important issue in a wide range of disciplines including economics, health care, adoption, political economy, insurance, worker safety, environmental impact assessment and globalization (Miller Ted R, 2000). A popular method of calculating the VSL is using government spending to assess how much is spent on life safeguarding (Gruber, 2011). In Table 7 an estimation of the VSL for some representative countries is reported.

Table 7. Representative Values of Life in different countries.

Country	Value of Life	Value of Life [USD]	Year	Reference
Australia	AUD 5.1MM	3.67MM	2021	(Best Practice Regulation Guidance Note: Value of Statistical Life, 2014)
New Zealand	NZ 4.14 MM	2.81MM	2016	(New Zeland Government Ministry of Transport, 2019)
Sweden	SEK 98 MM	10.80MM	2012	(Hultkrantz & Svensson, 2012)
Russia	USD 71.50K	71.50K	2015	(Технологий, 2015)
United States	USD 9.6MM	9.6MM	2016	(US Department of Transportation, 2016)

For the purpose of the article, an individual reference of VSL is assumed: the United States' USD 9.6MM. The reader should keep in mind that not always the presence and the evolution of defects leads to death. Consequently, to properly fill in the $\mathbb{Z}(\tilde{s}, s)$ matrix, the authors were required to assume a range of values for personal injury/damage. Considering the variability of possible defects, it is difficult to assign a specific monetary value to the associated DLs. For this reason, the authors tackled the problem with a mathematical approach rather than using specific values found in literature. In particular, a cubic distribution function was assumed because of its initial slow build up and its exponential growth when approaching collapse i.e. severe damage. Whilst different curves could be employed, the selected cubic non-linear behavior incorporates the higher aversion to fatality compared to any other level of injury. Figure 4a displays the above distributions in relation to the costs from which one can extrapolate the personal injury/fatality costs associated to each DL.



(a) (b)

Figure 4. Cost estimation model for: (a) personal injury and casualty and (b) maintenance cost and bridge replacement (BR). Red is used for the data and distributions assumed by the authors, whilst blue for the distribution assumed from literature.

Finally, to integrally fill the lower-left side of the $\mathbb{Z}(\tilde{s}, s)$ matrix (blue area in Table 6), it has also been necessary to research the costs of bridge reconstruction and maintenance. Estes and Frangopol (Estes & Frangopol, 1999) reported on a bridge system which is evaluated periodically and is repaired whenever the system reliability β falls below the target level. Their article includes an example in which the entire bridge had been replaced with its relative cost. For the purpose of the article, this value is assumed with a correction of the 1996 to 2023 inflation value. Therefore the considered cost to replace the entire bridge (BR) is equal to approximately USD 1.17MM. Estes and Frangopol (Estes & Frangopol, 1999) also provide different replacement/maintenance costs (see Figure 4b in blue) on the grounds of which, the authors performed a linear interpolation (in Figure 4b in red) and extrapolated the maintenance costs associated to each DL. Now that the maintenance/reparation costs and the injury/VSL costs have been determined, it is possible to fill Table 6, thus obtaining Table 8 i.e., the Penalty Matrix in terms of costs.

Table 8. Penalty Matrix in terms of costs filled in with values of life and reconstruction in USD.

In-situ Defect Grade (ISDG)	DL0	0	150K	1.20MM	4.05MM	9.6MM
	DL1	292.50K	0	150K	1.20MM	9.6MM
	DL2	585K	585K	0	150K	9.6MM
	DL3	877.50K	877.50K	877.50K	0	9.6MM
	DL4	1.17MM	1.17MM	1.17MM	1.17MM	0
		DL0	DL1	DL2	DL3	DL4
		Semantics-based Grade (SG)				

A limitation of the present work is the use of a single case study for the determination of the maintenance and reconstruction costs. For a more comprehensive evaluation of the performance of the novel inspection methodology a broader set of costs should have been introduced. This will be the focus of future work from the part of the authors. Finally, in the present subsection two types of Penalty Matrix were extracted on the basis of which the authors will be able, in the next subsection, to extract a single value of uncertainty-reduction benefit (in utility or costs, depending on the chosen $\mathbb{Z}(\tilde{s}, s)$) and to contextualize it in a broader perspective.

4.3 Expected Utility Theory to quantify the benefit of the inspective uncertainty reduction

In the present subsection the authors proceed to quantify the benefit achieved through the implementation of the novel Semantics-based Methodology and the consequent reduction in uncertainty. Furthermore, they contextualize the obtained Expected Utility values for the specific case study in a broader perspective in order to better grasp how the benefit varies as a function of the inspection quality (intended as influence of the representation-related uncertainty i.e., the ISDG/SG divergence). To achieve this, it is necessary to quantify, through Equation (2) (and Figure 3), the value of Expected Utility for each of the proposed Penalty Matrices (reported in Table 9a and b for clarity's sake).

Table 9. The two possible Penalty Matrices: (a) Pearson's one and (b) Penalty Matrix in terms of costs.

In-situ Defect Grade (ISDG)	DL0	0	1	4	9	16
	DL1	1	0	1	4	9
	DL2	4	1	0	1	4
	DL3	9	4	1	0	1
	DL4	16	9	4	1	0
		DL0	DL1	DL2	DL3	DL4
		Semantics-based Grade (SG)				

(a)

In-situ Defect Grade (ISDG)	DL0	0	150K	1.20MM	4.05MM	9.6MM
	DL1	292.50K	0	150K	1.20MM	9.6MM
	DL2	585K	585K	0	150K	9.6MM
	DL3	877.50K	877.50K	877.50K	0	9.6MM
	DL4	1.17MM	1.17MM	1.17MM	1.17MM	0
		DL0	DL1	DL2	DL3	DL4
		Semantics-based Grade (SG)				

(b)

Through the above steps the obtained Expected Utility values are:

- $\mathbb{E}[\mathbb{U}(s,\tilde{s})] = 0.74\ util$ in terms of Pearson's Index of Correlation (Figure 5a),
- $\mathbb{E}[\mathbb{U}(s,\tilde{s})] = 180\text{K}$ USD in terms of costs (Figure 5b).

The former provides information about the gravity of the ISDG/SG divergence. The latter displays the reduction in uncertainty in light of the adoption of a less-uncertain inspective methodology (the novel Semantics-based Methodology) and the consequent economic benefits for the inspection quality improvement. Whilst these two Expected Utility values provide a rather clear quantification of the ISDG/SG divergence, their true meaning cannot be really grasped without a benchmark comparison. Hence, the authors deem it necessary to contextualize them in a generalized perspective i.e., comparing them against a case study of minimum and maximum divergence. In the following, the authors introduce two Confusion Matrices whose divergence is designed to be minimum (Table 10a) and maximum (Table 10b).

Table 10. Confusion matrices which lead to obtain respectively (a) the minimum and (b) the maximum divergence.

In-sit Defect Grade (ISDG)						
	DL0	34	0	0	0	0
	DL1	0	63	0	0	0
	DL2	0	0	14	0	0
	DL3	0	0	0	1	0
	DL4	0	0	0	0	0
		DL0	DL1	DL2	DL3	DL4
		Semantics-based Grade (SG)				

(a)

In-sit Defect Grade (ISDG)						
	DL0	0	0	0	0	112
	DL1	0	0	0	0	0
	DL2	0	0	0	0	0
	DL3	0	0	0	0	0
	DL4	0	0	0	0	0
		DL0	DL1	DL2	DL3	DL4
		Semantics-based Grade (SG)				

(b)

Said matrices are representative of the minimal and maximal effect of the representation-related uncertainty on the inspective process. The minimum divergence (Table 10a) exists in light of the fact that all the content of the matrix is located on its main diagonal (ISDG=SG), regardless of the values themselves. Applying the Expected Utility Theory (Equation (2)) with said Confusion Matrix, one would obtain an Expected Utility $\mathbb{E}[\mathbb{U}(s,\tilde{s})] = 0\ util$ and $\mathbb{E}[\mathbb{U}(s,\tilde{s})] = 0$ USD. The maximum divergence is obtained only for a specific Confusion Matrix i.e., the one that has the total number of defects located in correspondence to the maximum value of the Penalty Matrix. Note that, whilst in Pearson's Penalty Matrix two maximum values exist (top-right and bottom-left cells as in Table 9a), in the cost-related one only a single maximum value exists (top-right cell in Table 9b). As such, the authors selected as maximum divergence matrix the one with the total number of defects located in the top-right cell (Table 10b). Proceeding in such a way, the consequent utility for the maximum ISDG/SG divergence is equal to $\mathbb{E}[\mathbb{U}(s,\tilde{s})] = 16\ util$ and $\mathbb{E}[\mathbb{U}(s,\tilde{s})] = 9.6$ MM USD. Now, with the values of Expected Utility of both maximum and minimum divergence, it is possible to contextualize the case study outputs ($0.74\ util$ and 180K USD) and assess the extent of their uncertainty-induced influence.

As previously mentioned, the ISDG/SG divergence quantified per Pearson's Correlation Index is a good measure of the weight of the representation-related uncertainty on the quality of the inspective process. As such, if to correlate the Expected Utility values represented in terms of costs and utility, one would obtain a correlation between costs and uncertainty-induced ISDG/SG divergences. In other words, through said correlation, it is possible to obtain the economic weight of the representation-related uncertainty. If to do so for the case study and the minimum/maximum divergence Confusion Matrices, an "Uncertainty-induced Cost curve" is extracted as in Figure 5.

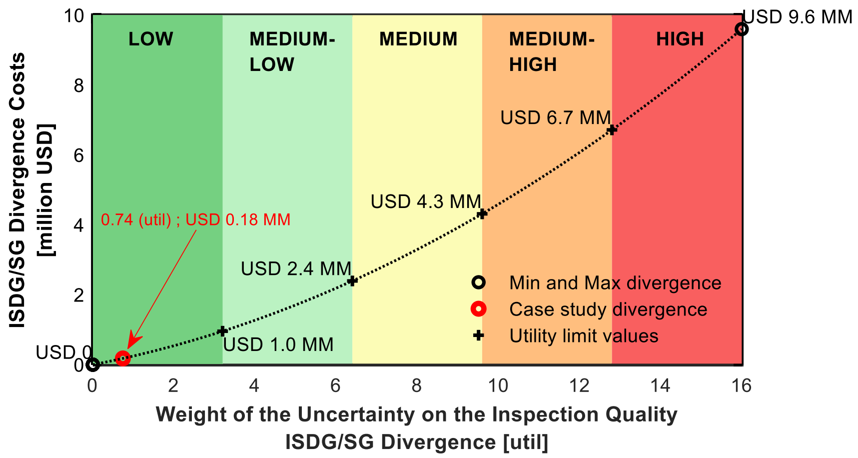


Figure 5. Uncertainty-induced Cost curve displaying the evolution of the costs as the extent of the divergence increases.

The Uncertainty-induced Cost curve was obtained through a quadratic-interpolation of the minimum and maximum divergence (in black in Figure 5) and the case study divergence (in red). Such interpolation has an initial slow build up and then grows exponentially, reflecting the fact that the costs due to the ISDG/SG divergence increase quickly as the effect of the uncertainty weights heavier on the inspection quality (illustrated also with a variation of background color). On the grounds of such curve the reader can finally grasp in a fast and intuitive way the evolution of costs as the effect of uncertainty on the inspection quality increases.

In light of this discussion, it can be stated that, compared to the minimum and maximum divergences, the case study set of inspections was minimally affected by representation-related uncertainty. Despite such, the reader should keep in mind that this result stems from a comparison with an extreme case (maximum divergence i.e., ISDG always ≠ SG and always 4-classes off). Indeed, as previously calculated, the representation-related uncertainty still affected the assignment of the Defect Grade in 50% of the cases resulting in an assumed cost of 180K USD, a non-neglectable amount. In light of such, the proposed Semantics-based Inspective Methodology represents an improvement over the current-day directly assigned condition grading one.

5. Conclusions

Numerous bridges worldwide have surpassed their design serviceability life. To ensure the safety of their users, visual inspections are commonly carried out with the consequent assignment of Defect Grades. These ones cover a key role in the preservation of infrastructural assets as, on their basis, simplified risk evaluations and maintenance intervention prioritizations are formulated. Per the inherent nature of the visual inspections, these ones include two kinds of uncertainty: an interpretation-related and a representation-related one. If one were to attempt to reduce their influence in the inspective process, the former could not be tackled as it is an intrinsic feature of inspections performed by humans. The latter, instead, can be decreased on the basis of a novel Semantics-based inspective methodology. The present article assesses the extent of the improvement in inspection quality in light of the above uncertainty reduction. The main points and conclusions are reported below:

- A case study of 46 bridges was taken in consideration. The grades of a certain number of defects were reported both in its direct assignment form (ISDG) and in its Semantics-based Inspective Methodology form (SG);
- An ISDG/SG correlation analysis was presented according to which 50% of the Defect Grades were affected by representation-related uncertainty, but only the 8% in a significant manner;
- Through the application of the Expected Utility Theory a single Expected Utility value was extracted for the present case study. This one was expressed in the form of utility and costs, helping to quantify the ISDG/SG divergence and therefore the influence of the representation-related uncertainty on the inspective process;

- A novel Uncertainty-induced Cost curve made it possible to assess the evolution of costs as a function of the weight of the representation-related uncertainty (varying inspection quality);
- The case study defect gradings appeared to be minimally affected by the representation-related uncertainty, but, despite such, the adoption of the Semantics-based Inspective Methodology would result in a benefit of 180K USD;

The proposed Semantics-based Inspective Methodology represents an improvement over the current-day directly assigned condition grading one. Hence, improving also the efficiency of structural reliability assessments, of bridge maintenance intervention prioritization and, finally, of bridge user safety. The planned future developments of the present research revolve around the alignment of the proposed methodology with the work of COST Action TU1406 (in particular, to its WG3 report) and the generalization of the costs that constitute the Penalty Matrix (e.g., different bridge materials, static schemes, etc.). In light of these two improvements, one can achieve an increased comprehensiveness of the novel methodology for quantifying the benefits of decreasing the overall uncertainty in the bridge condition assessment inspection practice.

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