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REGULAR PAPER

Evolutionary intelligence in asphalt pavement modeling and quality-of-information

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Abstract The analysis and development of a novel approach to asphalt pavement modeling, able to attend the need to predict the failure according to technical and non-technical criteria in a highway, is a hard task, namely in terms of the huge amount of possible scenarios. Indeed, the current state-of-the-art for service-life prediction is at empiric and empiric–mechanistic levels, and does not provide any suitable answer even for a single failure criteria. Consequently, it is imperative to achieve qualified models and qualitative reasoning methods, in particular due to the need to have first-class environments at our disposal where defective information is at hand. To fulfill this goal, this paper presents a dynamic and formal model oriented to fulfill the task of making predictions for multi-failure criteria, in particular in scenarios with incomplete information; it is an intelligence tool that advances according to the quality-of-information of the extensions of the predicates that model the universe of discourse. On the other hand, it is also considered the degree-of-confidence factor, a parameter that measures one‘s confidence on the list of characteristics presented by an asphalt pavement, set in terms of the attributes or variables that make the argument of the predicates referred to above.

Keywords Evolutionary intelligence · Extended logic programming · Knowledge representation and reasoning · Quality-of-information · An answer degree-of-confidence · Asphalt pavement modeling

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1 Introduction

The asphalt pavement performance prediction is essential to design new pavements as well as to manage the existing ones to keep the highway network in a good condition and to select the best cost-effective maintenance/rehabilitation solutions over an extended timeframe [1]. Modeling the asphalt pavement is among the biggest challenges of engineering. The consensus tells us about an intrinsic viscous-elastic-plastic non-linear and anisotropic behavior; very complex indeed, but not sufficient to explain the performance, suggesting the existence of more undiscovered parcels of the behavior or the inexistence of any kind of pattern. Apart from the intrinsic ones, the asphalt pavement behavior is subject to the interference of many external factors, such as the characteristics of the vehicles (e.g., speed, loads) and the environmental ones (e.g., temperatures, rainfall) [1,2].

Some methods and tools have been developed [3–6], and based, in general, on simplistic approaches with the performance characteristics represented by one or more empiric variables. On the other hand, due to the ultra-complex behavior of the asphalt pavement, worthwhile modeling cannot be achieved only with empirical or dogmatic approaches. A tool, able to handle all the necessary variables and its near infinite combinations needs to be used. The soft computing approach to modeling could be in line to provide the necessary power to this task [7,8]. However, it is a fact that the exercise of modeling the asphalt pavement task is difficult to judge, once it is based on the assessment of the list of characteristics presented by the environment, vehicles and structural behavior of the pavement, especially in environments with defective information. It is important to achieve qualitative models in order to offer support in decision-making processes, which is far behind the power of the connectionist approach.

Besides that, qualitative models and qualitative reasoning [9,10] have been around in Artificial Intelligence (AI) research for some time. In the last decades, a small, but growing number of studies have been made to apply some AI-based techniques to problem solving to asphalt pavements, looking for the performance prediction, pavement management and evaluation [11–13]. However, intelligent systems require the ability to reason with unknown and/or incomplete information, once in the real world complete information is hard to obtain, even in a controlled situation. The information is not always exact, but indeed imperfect, in the sense that we handle estimated values, probabilistic measures, or degrees of uncertainty [14].

On the other hand, logic and logic programs [15–17] have emerged as an attractive knowledge representation and reasoning formalism and as a promising approach to solving search problems in environments with defective information. Many non-classical techniques for modeling the universe of discourse and reasoning procedures for intelligent systems have been proposed [18–21]. One promising approach for knowledge representation and reasoning, in particular in scenarios with defective information, is a measure of the quality-of-information (QoI) associated to a logic program or theory, which may allow one to access the confidence on how much that theory or logic program models the universe of discourse [22–30].

In this work we present an evolutionary system, which outcomes go far behind the ones of the INTELLIPave [31] that was our first approach to asphalt pavement modeling. It allows us to predict the asphalt pavement behavior and service-life for multi-failure criteria, in particular when applied to scenarios with incomplete information [2,31]. It is based on an extension to logic programming (ELP), and presents itself as a pure symbolic system that adapts on the fly to the changes in the environment. Its computational entities are pictured as nodes in a network, in which occur logic inference processes which are driven by the QoI of the extensions of the predicates that model the universe of discourse, and the degree-of-confidence (DoC) that one has on the logic terms that make the theorem to be proved, i.e., each variable problem is linked to a particular scenario and takes a truth value on the range $0 \ldots 1$, which is a measure of the confidence on the information being used in the modulation process. With this approach, we are able to map the defective information associated to a particular problem in order to predict the asphalt pavement performance for a range of situations in terms of traffic, environment, and pavement thickness, the three factors that were considered in this work.

The paper is structured as follows. In the next section, we present the problematic of the asphalt pavement modeling process. In the section, three we present the semantics of the extended logic programming approach for knowledge representation and reasoning, as well as the QoI and DoC approaches. The section four presents the computational model, built on a novel approach to problem solving, that is supported by evolutionary intelligence-based techniques. Finally, we present the conclusions and the perspectives for the future work.

2 Asphalt pavement modeling

Modeling the service life for asphalt pavements is widely made with base on empirical methods, developed half-century ago, with poor results. The new reality of the twenty-first century, with high construction costs for materials and labor, environmental restrictions and growing volumes of vehicles in the highways enforce the shift to a new level of quality and accuracy to predict the service life of the pavements to have better cost-effective solutions [32].

2.1 The pavement challenge

It is widely accepted that one has to predict the asphalt pavement condition and performance with years in advance. This is critical to plan or estimate the budget, money-flow and engineering activities. Predicting the pavement serviceability is hard and complex, and in many cases are used subjective and unusual methods, because the current technologies do not provide any suitable solution. The task becomes even harder because, to make the engineering activities compatible (preventive or corrective maintenance, or major pavement rehabilitations) and the available budget, managers must define and set priorities involving the prediction of pavement condition assuming different criteria. In other words, the pavement failure scheme is a highly variable event depending not only on layer's material properties, sub-grade, environmental conditions and traffic load but also on the specific definition of failure adopted by the highway agencies, i.e., failure may be defined in terms of amount of cracking, rut depth, surface roughness, or combinations of these or other indicators of performance [33]. In fact, pavement managers need to work with several failure criteria including non-technical criteria, such as the highway property value, driver security and comfort, among others, and must try to maximize the efficiency for every used monetary unit. Constructing a complete and trustable system for asphalt pavement management, able to predict failure according to technical and non-technical criteria at the same time, is a hard task. Some protocols have been developed for asphalt pavement modeling [34–37] the USACE—US Army Corps of Engineers—and a kind of "generic" widely spread method known as empiric–mechanistic, where some considerations about the pavement mechanics are included in an empiric way. In general terms, these methods are very simplistic and based on empiric or empiric–mechanistic approaches, with the performance represented by two or three empiric variables (e.g., the ESAL, equivalent single axle loads, CBR, California bearing ratio) or the maximum strain in the asphalt concrete layer [35]. However, these approaches do not provide any suitable answer even for a single pavement failure criteria.

In the 1990s, the development of a new method for asphalt pavement modeling and design known as AASHTO 2002 was started, with the promise of by-pass many of the limitations of the existing methods. Contrary to the previous empiric methods, this new method is based on an empiric–mechanistic approach to evaluate the traffic, climate, subgrade and materials; the ESAL concept is removed and all vehicles with the respective climatic combination must to be evaluated. The built-in empiric–mechanistic models are not really new. The supposed better accuracy in fact depends on a complex model's calibration based on-field test sections that exist only in few States in USA, constructed under the LTPP Program (long-term pavement performance program). Due to its complicated calibration and not proven to have better accuracy, the AASHTO 2002 method did not become common even in the United States [36,37].

2.2 Related work

Some artificial intelligence (AI) studies about the management and evaluation of asphalt pavements have been presented, some of them centered in the field of geomechanics, with less emphasis on pavements. Tutumluer and Seyhan [38] used the artificial neural networks (ANNs), in particular the backpropagation method to predict the behavior of the granular materials submitted to triaxial test. Penumadu et al. [39] developed a model for argillaceous soils using ANNs. Penumadu and Zhao [40] used the feedback approach to model the behavior of the sands and gravels on the stress–strain relationship in triaxial. Basheer and Najjar [41] also used the multi-layer perceptron (MLP) to simulate the relation between stress and strain in fine soils using various types of loads. Using the sequential backpropagation approach, Ellis et al. [42] developed a model for sands based on the grading curve and tensions. Meier et al. [43] used the MLP for the backcalculation of pavements achieving a significant improvement of the performance. Ceylan et al. [44] used ANNs for the calculation of the stresses and deflections in joints of airport pavements as function of pavement thickness, base type and efficiency of the joints. Roberts and Attoh-Okine [45] used the ANNs with a quadratic function to predict the pavements roughness, i.e., the ANNs of quadratic functions is generalized, combining the supervised and self-organized learning procedures. Faghri and Hua [46] used adaptive resonance theory (ART) networks to group highways according with the monthly average daily traffic (MADT), with much better results than those achieved by traditional methods (regression and group analysis). Lingras [47] used Kohonen networks for a similar application, obtaining better performances when compared to the traditional hierarchical methods in the classification of traffic patterns.

The recognition of pavement defects in pavement images was studied by Xiao et al. [48], who developed an algorithm called DENSITY-based neural network, DNN which, according with the authors, in tests realized with 83 real pavement images, achieved the accuracy of 97.5% in the detection. A similar work was developed by Bray et al. [49] using two ANNs in hierarchical fashion, one to detect the existence (or not) of defects, and the second to classify the existing defects, working with properties of images as the histograms.

In Abdallah et al. [50], the MLP is used to estimate the remaining service-life of the asphalt pavements on the fatigue cracking and rutting using deflection data of the falling weight deflectometer (FWD) and layer thicknesses as inputs.

Miradi [51] evaluated 60 scientific studies that employed AI-based techniques to study the various aspects of the pavements between 1995 and 2007. Of these, 2% addressed the loss of aggregates in the asphalt layer (raveling); 18% reported to the cracking; 3% about plastic deformations (rutting); 7% about the surface roughness of the pavement; 27% described the combination of cracking, rutting and roughness; while 43% were related to structural modulus of the pavement layers, i.e., 12% used the classification method, while 88% used the regression technique. However, none of the 60 studies made the simultaneous study or combination of the characteristics of the materials, traffic and climatic factors [51]. Using information on The Netherlands, Miradi (2009) [51] developed an interesting work to identify the most important factors for the degradation of the asphalt pavement using ANNs, support vector machine (SVM), genetic algorithms, decision trees and rough sets, for the prediction of cracking occurrence, rutting and loss of aggregate for asphalt layers with different ages.

In China, Cal [52] used the ANNs to classify the pavements, using three basic factors—the plasticity index, the liquid limit and the clay content, to classify six different types of soils. The ANNs were trained using the backpropagation algorithm and the ANNs presented 100% of accuracy in the predictions. In Italy, Bosurgi et al. [8] achieved good results in the development of a model to predict the tire–pavement friction force (sideway force coefficient, SFC) in Italian highways using ANNs [53,54] as well as in models to predict the highways accidents [53]. In South Africa Venayagamoorthy et al. [55] used ANNs to classify different types of pavement structures according to the highway category, class of traffic and type of base layer; in the 30 studies, the ANNs were able to realize the classification without any error. In India Thube et al. [56] developed a work about the use of ANNs for the prediction in the damage of road pavements with small volume of vehicles. In USA (State of Illinois), a research was undertaken using ANNs and Genetic Algorithms to evaluate the pavement structure through non-destructive tests, with special emphasis on backcalculation [57]. Again in the Illinois State, the application of ANNs was studied to predict the modulus for airport asphalt pavements using data sets acquired with heavy weight deflectometer (HWD), which is an equipment similar to the FWD, however, able to apply heavier loads [58].

Bianchini and Bandini [59] used neuro-fuzzy reasoning to predict the asphalt pavements behavior using deflection data read with FWD and the pavement surface distresses. In Turkey, Taskiran [60] used the ANNs and the gene expression programming (GEP) to predict the values of the California bearing ratio (CBR). Also in Turkey, Tapkin et al. [61] developed an interesting study for the prediction of the Marshall properties in cores of asphalt concrete modified with polypropylene fiber using ANNs trained with the backpropagation algorithm. Bayrak et al. [62] used the ANNs to predict the International Roughness Index (IRI) in rigid pavements; they used 83 data sets from long-term pavement performance program (LTPP). The variables used include (on the input layer) the initial IRI, the age of the pavement, the traffic and the transverse cracks for three levels of severity (low, medium and high); as output variable was used the IRI measured in the pavements. The developed model was able to predict the IRI values with a high accuracy. Aultman-Hall et al. [63] used ANNs and other statistical techniques to study the correlations between the IRI and the cracked area and rutting based on data collected on 650 km of highways. The objective was to verify the possibility to use the IRI to estimate the pavement distresses.

2.3 Handling incomplete information in an asphalt pavement setting

Until now, the INTELLIPave method [2,31] was our proposal for asphalt pavement modeling, where a very large amount of data was used in order to build a model based on AI-based techniques. That data were collected using sensors over large periods of time (10 or more years). The data had all kinds of problems, from lack of data to unreal data due to a large set of problems, like sensors failure, sensor loss of accuracy, sensor replacement or miscalibration, hardware and software failure to register the data, just to name a few. Those problems have negative impact in any model being built. The INTELLIPave method itself was built with ways for error handling and consideration of unknown variables, in terms of a soft-computing approach to problem solving, using ANNs, but was far behind of being considered as a reference.

In conclusion, a method that involves evolution and is able to deal with incomplete information on a formal basis [17,64] is presented and discussed in this paper.

3 Knowledge representation and reasoning and quality-of-information

Several non-classical techniques to model the universe of discourse and reasoning procedures of intelligent systems have been proposed [15,19,65], many of them being based on logic with probability theory, combining the Bayesian reasoning with multi-value logics [21,66], theory of evidence (Dempster–Shafer) [18], fuzzy logic [20], and hybrid formalisms, just to name a few. Then again, logic programming (LP) has emerged as an attractive formalism for knowledge representation and reasoning tasks, introducing an efficient mechanism for solving search problems. Therefore, and in order to exemplify the applicability of our model, we will look at the relational database model, since it provides a basic framework that fits into our expectations [67].

Fig. 1 An Extension of the relational database model

pavement

#	Highway_ID	Pavement_Type	Thickness_Value
1.	1	asphalt_concrete_A	{100,150,200}
2.	2	asphalt_concrete_B	120
3.	3	asphalt_concrete_C	85

vehicles

#	Highway ID	Struct_resp ID	vehicles_per_ day_Value
1.	1	50	{11000,14000}
2.	2	51	⊥
3.	3	52	15000

climate

#	Climate _ID	Highway _ID	Struct_resp _ID	Climate_Type	Air_Temperature _Value
1.	1	3	52	climate_type_1	25
2.	2	1	50	climate_type_2	⊥
3.	3	2	51	climate_type_3	43

Asphalt_structural_response

#	Struct_resp _ID	Structural_resp_ Type	Structural_ resp_Value	cracked_area Value
1.	50	aStruct_R_type_1	100	{33,42}
2.	51	aStruct_R_type_2	70	34
3.	52	aStruct_R_type_3	55	63

Consider, for instance, the scenario where a relational database is given in terms of the four relations presented in Fig. 1. It denotes a situation where one has to store and manage information about asphalt pavement modeling, namely the pavements, vehicles, and climate, and the asphalt structural response. In this scenario, some incomplete data are also presented on the extensions of some relations. For instance, for pavement "1" the thickness value is unknown, although it is one of the elements of the set {100, 150, 200}; for highway "2" the vehicles per day value is unknown.

3.1 Knowledge representation and reasoning

Many approaches for knowledge representation and reasoning have been proposed using the LP paradigm, namely in the area of Model Theory [15,68,69], and Proof Theory [17,68,70]. We follow the proof theoretical approach and an extension to the logic programming language [17], to knowledge representation and reasoning. An extended logic program (ELP for short) is a finite set of clauses in the form:

$$q \leftarrow p_1 \wedge p_n \wedge not q_1 \wedge \ldots \wedge not q_m \qquad (1)$$

$$?p_1 \wedge \ldots \wedge p_n \wedge not q_1 \wedge \ldots \wedge not q_m (n, m \geq 0) \qquad (2)$$

where ? is a domain atom denoting falsity, the p_i, q_j, and p are classical ground literals, i.e., either positive atoms or atoms preceded by the classical negation sign [70]. In this representation formalism, every program is associated with a set of abducibles [15,69], given here in the form of exceptions to the extensions of the predicates that make the program.

To reason about the body of knowledge presented in a particular set, that considers incomplete information on the base of the formalism referred to above, let us consider a procedure given in terms of the extension of a predicate denoted as demo [15,17]. This meta predicate is given by the signature demo:T,V $\longrightarrow$ {true, false, unknown, according to the following set of terms:

```
demo(T, true) ← T.
demo(T, false) ← ¬T.
demo(T, unknown) ← not T,
                   not¬T.
```

Under this scenario, the first clause establishes that a theorem to be proved is put to a knowledge base of positive information returning the truth-value true (1); the second clause denotes that the theorem to be proved recurred to the negative information presented in the knowledge base, returning the truth-value false (0); the third clause stands for itself, associating the theorem to be proved with a truth-value in the interval]0,1[, i.e., a measure of system confidence in the proof process.

As a simple example, let us consider the relations given in Fig. 1, and rewrite them in terms of the predicates:

```
pavement: Highway_ID x Pavement_Type x Thickness_Value
climate: Climate_ID x Highway_ID x Struct_resp_ID x Climate_Type x
         Air_Temperature_Value
vehicles: Highway_ID x Struct_resp_ID x vehicles_per_day_Value
asphalt_structural_response: Struct_resp_ID x Struct_resp_Type x
                             Struct_resp_Value x cracked_area_Value
```

It is now possible to give the extensions of the predicates referred to above, which may be set in the form:

Program 1: The extended logic program for predicate *pavement*

```
{
  ¬ pavement(X,Y,Z)← not pavement(X,Y,Z),
                     not abducible_pavement(X,Y,Z).
  pavement(2,asphalt_concrete_B,120).
  pavement(3,asphalt_concrete_C,85).
  abducible_pavement(1,asphalt_concrete_A,100).
  abducible_pavement(1,asphalt_concrete_A,150).
  abducible_pavement(1,asphalt_concrete_A,200).
}
```

In program 1, the first clause denotes the closure of the predicate pavement. The second and third clause denote that the thickness values for the highway with the naming

2 and 3, and for the type of pavement asphalt_concrete_B and asphalt_concrete_C, are 120 and 85, respectively. The fourth, fifth, and sixth clauses denote that the thickness_value for the highway 1 and pavement-type asphalt_concrete_A is unknown, but its values are in the set {100, 150, 200, {100, 150}, {100, 200}, {150, 200}, {100, 150, 200}}.

Program 2: The extended logic program for predicate *climate*

```
{
  ¬ climate(V,W,X,Y,Z)← not climate(V,W,X,Y,Z),
                        not abducible_climate(V W,X,Y,Z).
  abducible_climate(V,W,X,Y,Z) ←climate(V,W,X,Y,⊥).
  climate(2,1,50,climate_type_2, ⊥).
  climate(1,3,52,climate_type_1,25).
  climate(3,2,51,climate_type_3, 43).
}
```

In program 2, the first clause denotes the closure of the predicate climate. In the second and third clauses the symbol '⊥' stands for a null value, that subsumes that variable Z stands for any value in the Z domain. The fourth and fifth clauses denote that the value of climate for the highway with the naming 1 and 3 and for the climate types, climate_type_1 and climate_type_3 are 25 and 43, respectively.

Program 3: The extended logic program for predicate *vehicles*

```
{
  ¬ vehicles(X,Y,Z)← not vehicles(X,Y,Z),
                     not abducible_vehicles(X,Y,Z).
  abducible_vehicles(X,Y,Z) ←vehicles(X,Y,⊥).
  vehicles(2,51, ⊥).
  vehicles(3,52,15000).
  abducible_vehicles(1,50,11000).
  abducible_vehicles(1,50,14000).
}
```

Program 4: The extended logic program for predicate asphalt_structural_response("asr" for short)

```
{
  ¬ asr(W,X,Y,Z)← not asr(W,X,Y,Z),
                   abducible_asr(W,X,Y,Z).
  asr(51,aStruct_R_type_2,70,34).
  asr(52, aStruct_R_type_3,55,63).
  abducible_asr(50, aStruct_R_type_1,100,33).
  abducible_asr(50, aStruct_R_type_1,100,42).
  ?((abducible_asr(W1,X1,Y1,Z1) ∨
    abducible_asr(W2,X2,Y2,Z2)) ∧
    ¬ (abducible_asr(W1,X1,Y1,Z1) ∧
      abducible_asr(W2,X2,Y2,Z2)
    ))
}
```

In program 4, the fourth and fifth clauses denote the fact that the values of the cracked area of the asphalt_structural_response for the term with a structural response of 100 is either 33 or 42, but not both, i.e., the sixth clause states that the value of cracked area is either 33 or 42, but not both.

It is now possible to engender all the possible scenarios to represent the universe of discourse, based on the information given in the logic programs 1, 2, 3 and 4 and their QoI.

3.2 Quality-of-information

Due to the growing need to offer user support in decision-making processes some studies have been presented [71,72], related to the qualitative models and qualitative reasoning in Database Theory and in AI research. With respect to the problem of knowledge representation and reasoning mechanisms in LP, a measure of the quality-of-information (QoI) of such programs has been object of some work with promising results [73–75]. The QoI [17] with respect to the extension of a predicate i will be given by a truth-value in the interval [0,1], i.e., if the information is known (positive) or false (negative) the QoI for the extension of predicate i is 1. For situations where the information is unknown, the QoI is given by:

$$\mathrm{QoI}_i = \lim_{N\to\infty} \frac{1}{N} = 0 (N \gg 0) \tag{3}$$

where N denotes the cardinality of the set of terms or clauses of the extension of predicate i that stand for the incompleteness under consideration. For situations where the extension of predicate i is unknown but can be taken from a set of values, the QoI is given by:

$$\mathrm{QoI}_i = 1/\mathrm{Card} \tag{4}$$

where Card denotes the cardinality of the abducibles set for i, if the abducibles set is disjoint. If the abducibles set is not disjoint, the QoI is given by:

$$\mathrm{QoI}_i = 1 \Big/ \left(C_1^{\mathrm{Card}} + \cdots + C_{\mathrm{Card}}^{\mathrm{Card}} \right) \tag{5}$$

where $C_{\mathrm{Card}}^{\mathrm{Card}}$ is a card-combination subset, with Card elements. The next element of the model to be considered is the relative importance that a predicate assigns to each of its attributes under observation, i.e., w_i^k, which stands for the relevance of attribute k in the extension of predicate i. It is also assumed that the weights of all the attribute predicates are normalized, i.e.:

$$\sum_{1\le k\le n} w_i^k = 1, \forall i \tag{6}$$

where, ∀ denotes the universal quantifier. It is now possible to define a predicate's scoring function $V_i(x)$ so that, for a value $x = (x_1, \ldots, x_n)$ in the multi-dimensional space, defined in terms of the attributes of predicate i, one may have:

$$V_i(x) = \sum_{1\le k\le n} w_i^k \times \mathrm{QoI}_i(x)/\mathrm{n} \tag{7}$$

It is now possible to engender all the possible scenarios of the universe of discourse, according to the information given in the logic programs 1, 2, 3 and 4. For example, one may have (Fig. 2).

The dashed slices in the circle are built on the extensions of the predicates referred to above, namely pavement, vehicles, asphalt structural response, and climate, and denote the QoI that is associated with each of the predicates. In practical terms, at the end of the process we will get a set of theories (or scenarios) that correspond to the best models of the universe of discourse.

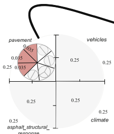
It is now feasible to rewrite the extensions of the predicates referred to above, in terms of a set of possible scenarios (here it will be presented 2 (two) of such scenarios), according to productions of the type:

$$\text{predicate}_i((\text{QoI}, x_1, \ldots, x_n), \text{DoC}) \tag{8}$$

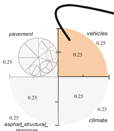
where DoC = Vi(x1, …, xn)/n denotes the one's confidence on a particular term of the extension of predicate i, leading to:

Program 1: Scenario 1 for the highway 1

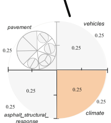
```
{
¬pavement(V,X,Y,Z,R)← not pavement(V,X,Y,Z,R)
pavement(0.035,1, asphalt_concrete_A, 100, 0.77), once
```



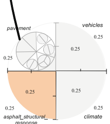
```
QoI_Thickness_Value=1 x 0.33=0.3 and
V_pavement(0.035,1,asphalt_concrete_A,100)=(1+1+0.3)/3 = 0.77
pavement(0.035,2, asphalt_concrete_B,120,1)once
QoI_Thickness_Value = 1 x 1 = 1 and
V_pavement(0.035,2,asphalt_concrete_B,120) = (1+1+1)/3 = 1
pavement(0.035,3,asphalt_concrete_C,85,1) once
QoI_Thickness_Value = 1 x 1 = 1 and
V_pavement(0.035,3,asphalt_concrete_C,85) = (1+1+1)/3 = 1
¬vehicles(V,X,Y,Z,R)← not vehicles(V,X,Y,Z,R)
vehicles(0.25,1,50,11000,0.83), once
```



```
QoI_vehicles_per_ day_Value = 1 x 0.5 = 0.5 and
V_vehicles(0.25,1,50,11000) = (1+1+0.5)/3 = 0.83
vehicles(0.25,2,51,true,0.66), once
QoI_vehicles_per_ day_Value = 0 x 1 = 0 and
V_vehicles(0.25,2,51,true) = (1+1+0)/3 = 0.66
vehicles(0.25,3,52,15000,1), once
QoI_vehicles_per_ day_Value = 1 x 1 = 1 and
V_vehicles(0.25,3,52,15000) = (1+1+1)/3 = 1
¬climate(V,W,X,Y,Z,W,H) ← not climate(V,W,X,Y,Z,W,H)
climate(0.25,1,3,52,climate_type_1,25,1), once
```



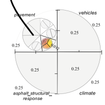
```
QoI_Air_Temperature_Value = 1 x 1 = 1, and
V_climate(0.25,1,3,52,climate_type_1,25) = (1+1+1+1+1)/5 = 1
climate(0.25,2,1,50,climate_type_2,true,0.8), once
QoI_Air_Temperature_Value = 1 x 0 = 0, and
V_climate(0.25,2,1,50,climate_type_2,true)=(1+1+1+1+0)/5=0.8
climate(0.25,3,2,51,climate_type_3,43,1), once
QoI_Air_Temperature_Value = 1 x 1 = 1, and
V_climate(0.25,3,2,51,climate_type_3,43) = (1+1+1+1+1)/5 = 1
¬asr(V,X,Y,Z,W,R) ← not asr(V,X,Y,Z,W,R)
asr(0.25,50, aStruct_R_type_1,100,33,0.88), once
```



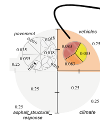
```
QoI_Cracked_area_value= 1 x 0.5 = 0.5, and
V_asr(0.25,50, aStruct_R_type_1,100,33)=(1+1+1+0.5)/4=0.88
asr(0.25,51, aStruct_R_type_2, 70,34,1), once
QoI_Cracked_area_value= 1 x 1 = 1, and
V_asr(0.25,51, aStruct_R_type_2,70,34) = (1+1+1+1)/4 = 1
asr(0.25,52, aStruct_R_type_3,55,63,1), once
QoI_Cracked_area_value= 1 x 1 = 1, and
V_asr(0.25,52, aStruct_R_type_3,55,63) = (1+1+1+1)/4 = 1
}
```

Program 7: Scenario 7 for the highway 1

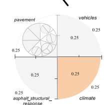
```
{
¬pavement(V,X,Y,Z,R)← not pavement(V,X,Y,Z,R)
pavement(0.012,5,1,asphalt_concrete_A,100,0.77),once
```



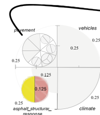
```
QoI_Thickness_Value = 1 x 0.33 = 0.3 and
V_pavement(0.012,5,1,asphalt_concrete_A,100)=(1+1+0.3)/3=0.77
pavement(0.012,2, asphalt_concrete_B,120,1)once
QoI_Thickness_Value = 1 x 1 = 1 and
V_pavement(0.012,2,asphalt_concrete_B,120) = (1+1+1)/3 = 1
pavement(0.012,3,asphalt_concrete_C,85,1) once
QoI_Thickness_Value = 1 x 1 = 1 and
V_pavement(0.012,3,asphalt_concrete_C,85) = (1+1+1)/3 = 1
¬vehicles(V,X,Y,Z,R)← not vehicles(V,X,Y,Z,R)
vehicles(0.083,1,50,11000,0.83), once
```



```
QoI_vehicles_per_ day_Value = 1 x 0.5 = 0.5 and
V_vehicles(0.083,1,50,11000) = (1+1+0.5)/3 = 0.83
vehicles(0.083,2,51,true,0.66), once
QoI_vehicles_per_ day_Value = 0 x 1 = 0 and
V_vehicles(0.083,2,51,true) = (1+1+0)/3 = 0.66
vehicles(0.083,3,52,15000,1), once
QoI_vehicles_per_ day_Value = 1 x 1 = 1 and
V_vehicles(0.083,3,52,15000) = (1+1+1)/3 = 1
¬climate(V,W,X,Y,Z,W,H) ← not climate(V,W,X,Y,Z,W,H)
climate(0.25,1,3,52,climate_type_1,25,1), once
```



```
QoI_Air_Temperature_Value = 1 x 1 = 1, and
V_climate(0.25,1,3,52,climate_type_1,25) = (1+1+1+1+1)/5 = 1
climate(0.25,2,1,50,climate_type_2,true,0.8), once
QoI_Air_Temperature_Value = 1 x 0 = 0, and
V_climate(0.25,2,1,50,climate_type_2,true) = (1+1+1+1+0)/5 =
0.8
climate(0.25,3,2,51,climate_type_3,43,1), once
QoI_Air_Temperature_Value = 1 x 1 = 1, and
V_climate(0.25,3,2,51,climate_type_3,43) = (1+1+1+1+1)/5 = 1
¬asr(V,X,Y,Z,W,R) ← not asr(V,X,Y,Z,W,R)
asr(0.125,50, aStruct_R_type_1,100,33,0.88), once
```



```
QoI_Cracked_area_value= 1 x 0.5 = 0.5, and
V_asr(0.125,50,aStruct_R_type_1,100,33)=(1+1+1+0.5)/4=0.88

asr(0.125,51, aStruct_R_type_2, 70,34,1), once
QoI_Cracked_area_value= 1 x 1 = 1, and
V_asr(0.125,51, aStruct_R_type_2,70,34) = (1+1+1+1)/4 = 1
asr(0.125,52, aStruct_R_type_3,55,63,1), once
QoI_Cracked_area_value= 1 x 1 = 1, and
V_asr(0.125,52, aStruct_R_type_3,55,63) = (1+1+1+1)/4 = 1
}
```

4 Evolving systems

The architecture of the computational model, named virtual intellect, is structured in terms of a set of entities denoted as symbolic neurons. To each neuron is associated a logic program or theory that models the view that such entities have of the whole system, given by the extensions of the predicates that make their corpus. The input of each neuron is given as a list of sub-problems to be solved according to the diverse scenarios referred to above. Indeed, the evolutionary process starts with an approximate representation of the universe of discourse and proceeds in order to maximize the DoC that is associated with each term in the extensions of the predicates (Figs. 3, 4).

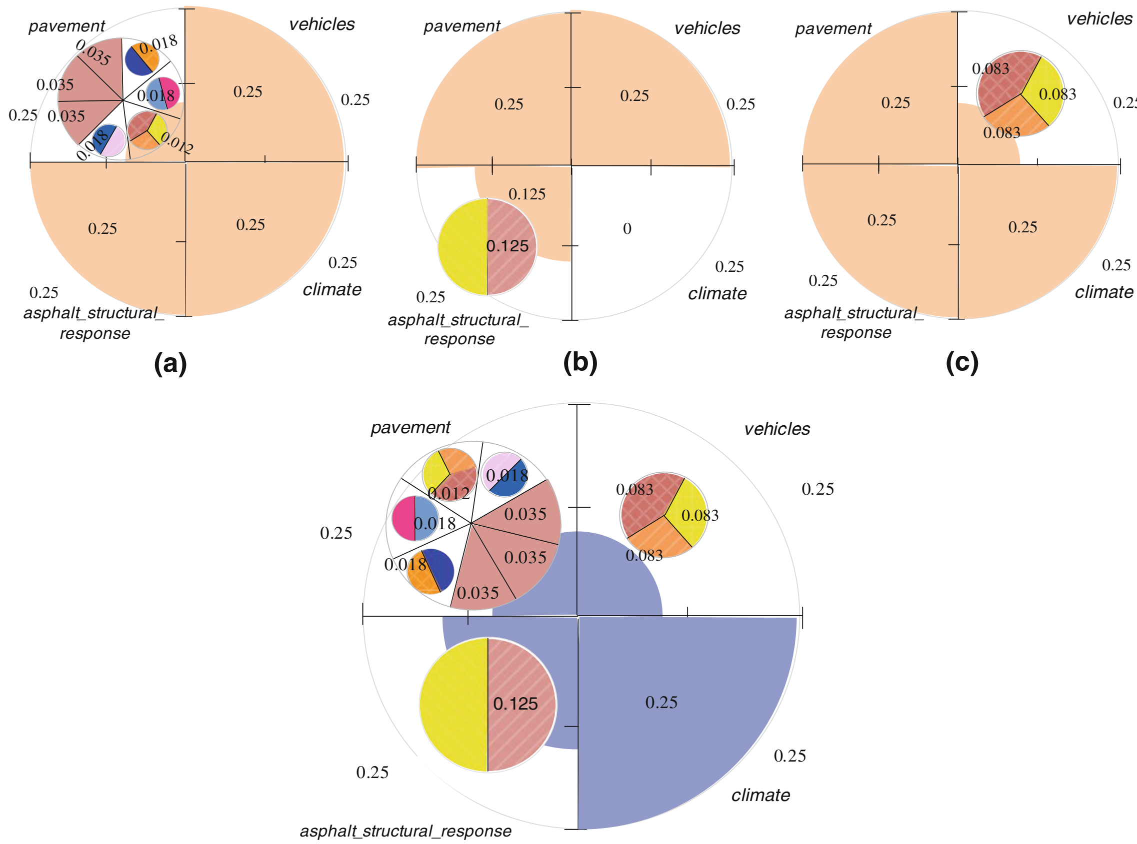
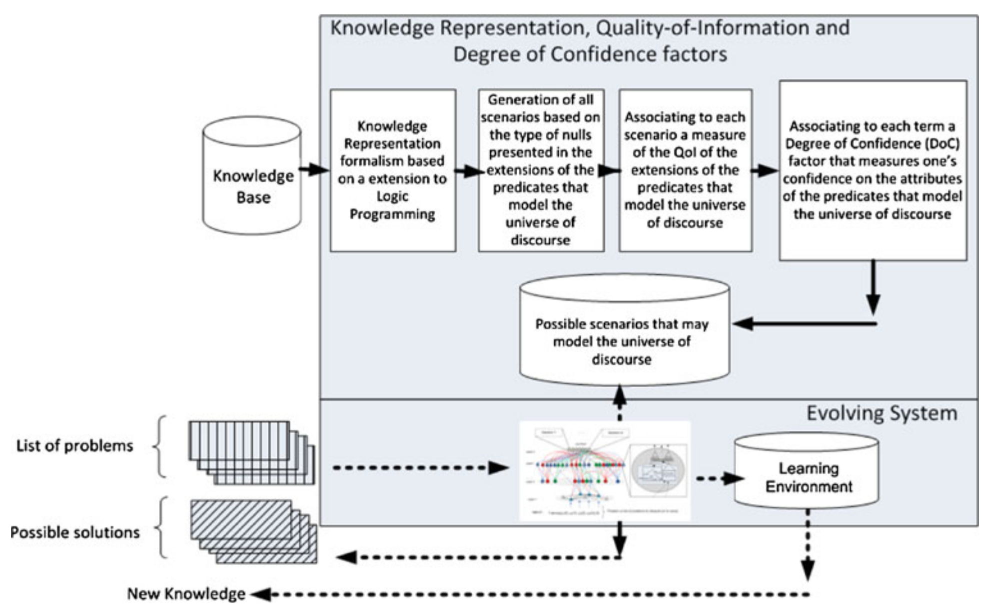


Fig. 2 A representation of some of the possible scenarios

Fig. 3 The Virtual intellect process of evolution



For example, given the question *Which are the pavements that may have an asphalt structural response with an accuracy of 100%?,* which is presented to the system in the form (Fig. 5).

$$\forall(A, B, C, E, V, S, N, H, L)), \\ ?demo((pavement(A, B, C), (vehicles(A, E, V),\ V > 0), \\ asr(E, S, 100, H)), L). \tag{9}$$

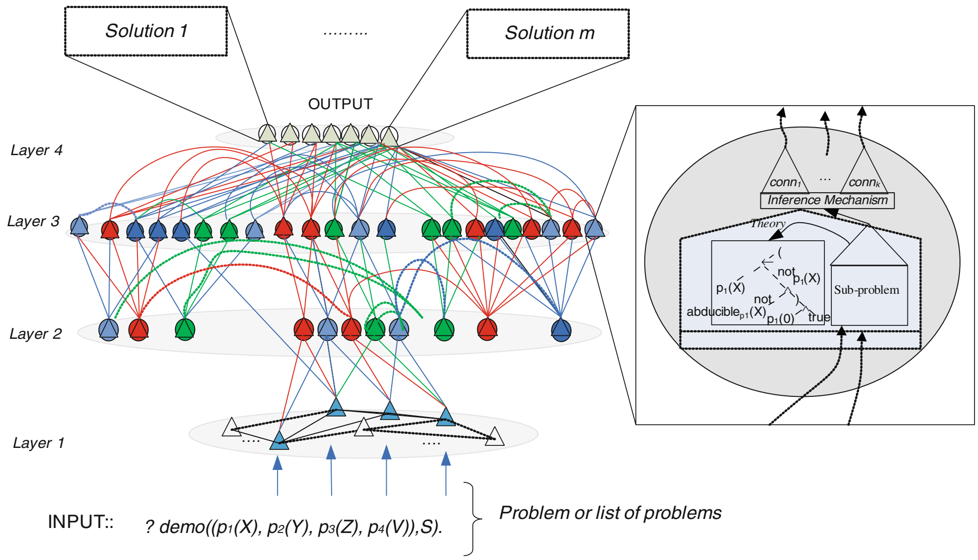


Fig. 4 A schematic representation of a virtual intellect

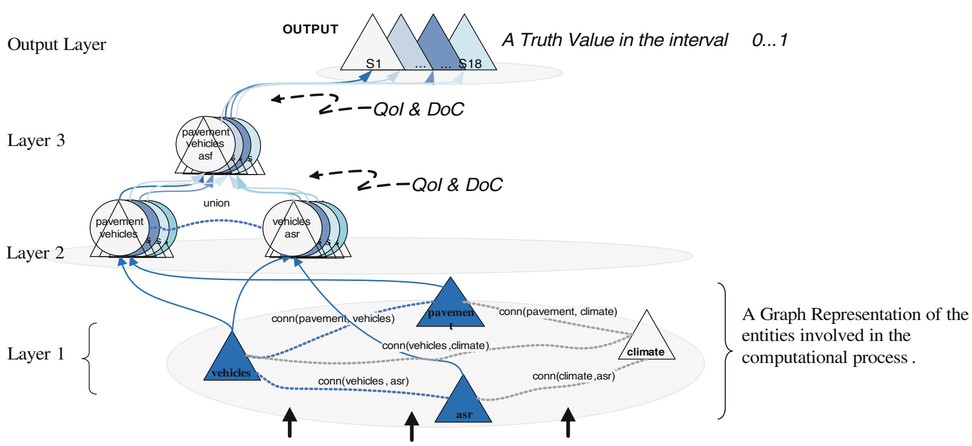


Fig. 5 Instantiation of the virtual intellect at $t = 1$

If the output layer has more than one neuron, it means that there are different theories that model the universe of discourse, being selected the one that presents the best *DoCs* in each term in the extensions of the predicates. On the other hand, in terms of evolution three new entities were created as a consequence of the two connections that were established between the extensions of the predicates *pavement* and *vehicles* and between *vehicles* and *asr*, and expressed in the form:

$$pavement(0.035, 1, asphalt\_concrete\_A, 100, 0.77).$$
$$vehicles(0.25, 1, 50, 11000, 0.83).$$
$$asr(0.25, 50, aStruct\_R\_type\_1, 100, 33, 0.88).$$

4.1 The genome

It is well known that an evolutionary algorithm (EA) is made of a set of computational mechanisms that follow the fundamentals of the Darwinist theory. In these systems, during the course of evolution, the phenotype is the basis for the assessment of an individual. Each neuron is coded with two types of genes, namely processing genes that specify how each neuron will evaluate its output, and a set of connection genes which specify the potential connections to other neurons, built in terms of the extensions of the remaining predicates that model the universe of discourse. In Fig. 6 we present an example of a hypothetical genome.

On the other hand, the processing genes determine how each neuron translates the input in output, i.e., considering that $P(t)$ denotes a particular population at a specific time t, one may have:

$$P(t) = \langle \{gp_1(t), [gc_1(t), \ldots, gc_k(t)]\}, \ldots \{gp_1(t), [gc_1(t), \ldots, gc_k(t)]\} \rangle \quad (10)$$

where, each individual is composed by a set of processing genes ($gp_n(t)$) and one or more connection genes ($gc_k(t)$).

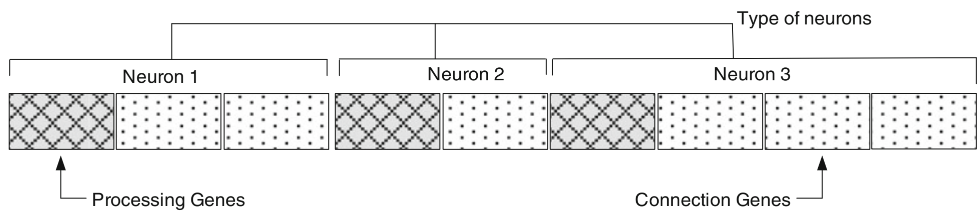


Fig. 6 Example of a hypothetical genome

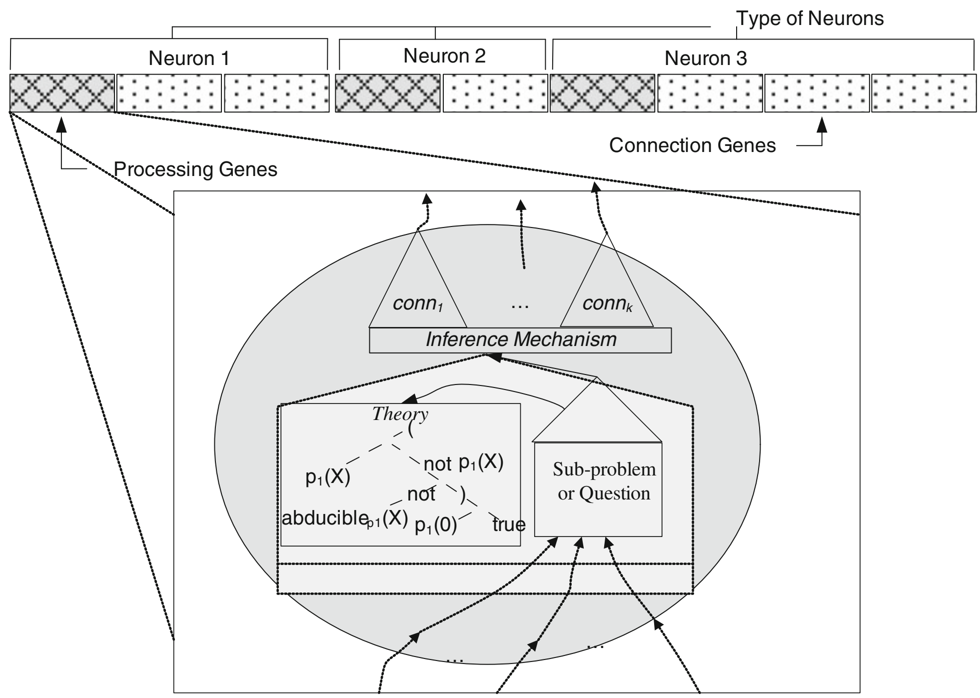


Fig. 7 Schematic of a processing gene

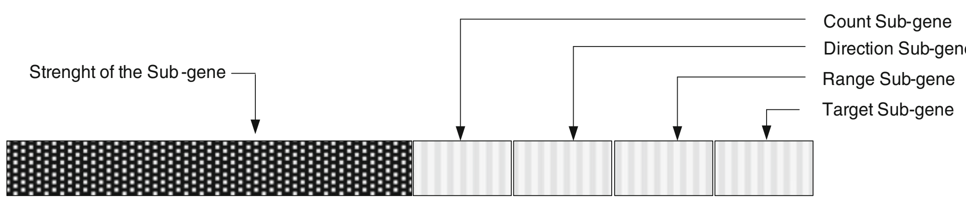


Fig. 8 Schematic of the connection genes

4.2 The processing genes

In the processing genes, we find the extensions of the predicates, invariants, structural and relationship dependencies, and inference mechanisms that make the realm of each neuron (Fig. 7).

4.3 The connection genes

The connection genes are encoded as five sub-genes, namely *count, direction, range* and *target* (Fig. 8).

The connection gene determines how each gene may be connected to others, according to the QoI of the connection, i.e., the genes may be structured as follows:

$$gc_n(t) = \{[connection(p, q), state, QoI], \quad count, direction, range\} \tag{11}$$

where *connection(p, q)* stands for the connection between the extensions of the predicates p and q according to their relationship of dependency, and *state* denotes the state of the connection. The last three arguments, here coded as *count, direction* and *range* set the path to the next neuron where the inference process will proceed. At this stage (i.e., $t=1$), the genome of the virtual intellect will present the form (Figure 9):

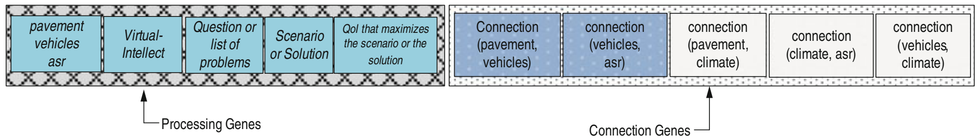


Fig. 9 The virtual intellect genome at $t = 1$

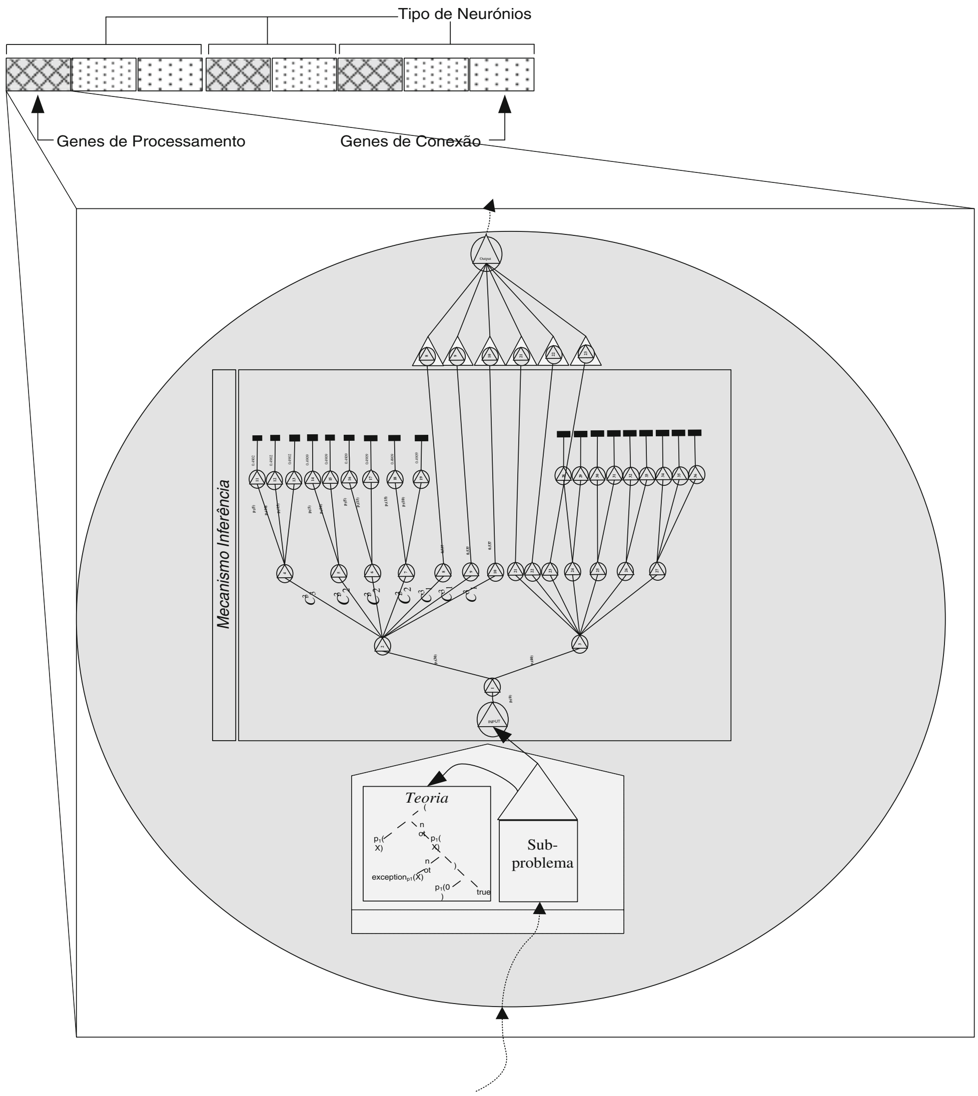


Fig. 10 Exemplification of the inference process—integration into the genome

4.4 The evolutionary process

The pseudo-code of the evolutionary algorithm is given below (Fig. 11).

Algorithm: Generation of the Evolutionary Network (Scenario, Problem, DoC)

1. Consider a given scenario or logic theory:
   Theory ←InferenceProcess(Scenario,Problem);
2. Randomly generate the initial population P(i) at the instant i = 1:
   $P(i)$ ←Generate_Population(Set_of_Theories, Problem);
3. Evaluate each individual (at instant i = 1):
   New_Population_DoC←apply_DoC_Measure(P(i), DoC);
4. Generate connections:
   Generate_Connections(New_Population,Connections);
5. *While DoC ≤ Reference_Value Do*
6. *Select parents from P(i) based on the evaluation of P(i);*
7. *Apply the reproduction operator to parents and produce offspring. The next generation P(i+1) is obtained from the offsprings and from the possible parents.*
8. Evaluate each individual;
   New_Population_DoC← apply_DoC_Measure(P(i), DoC);

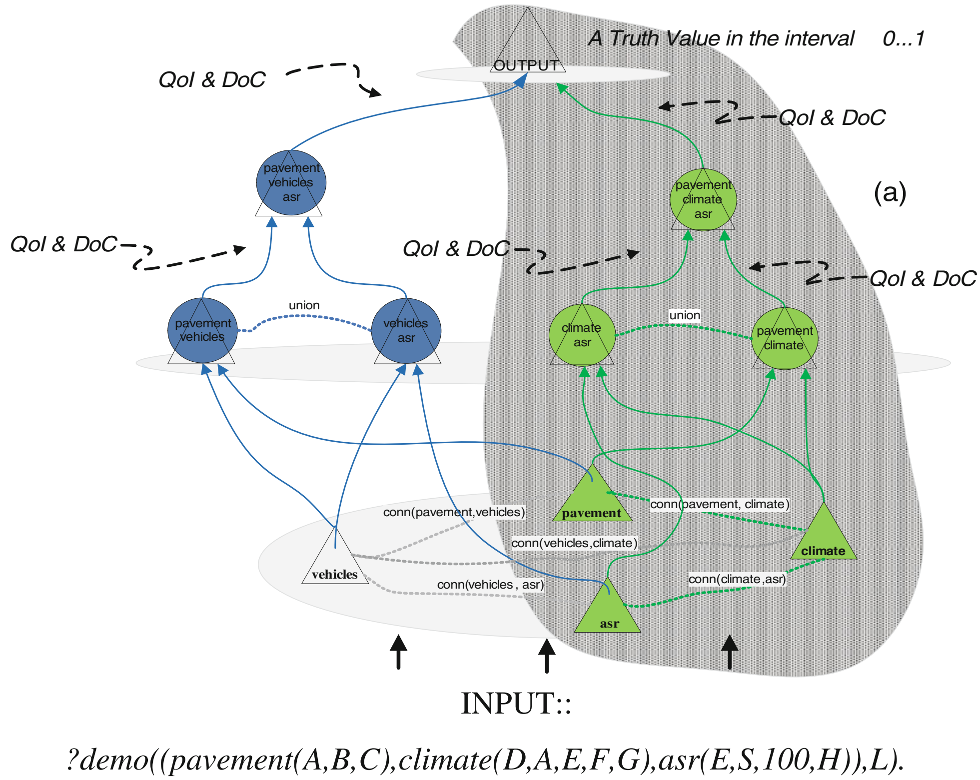


Fig. 11 Creation of the virtual intellect for the question in a moment $t=2$

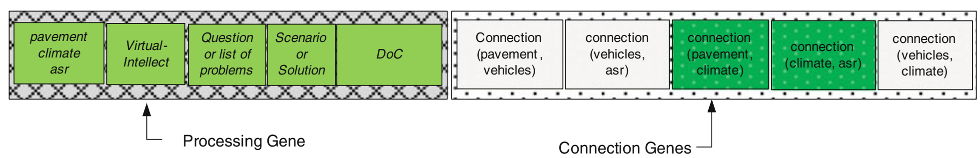


Fig. 12 The virtual intellect genome at $t=2$

9. Generate connections:
   Generate_Connections(New_Population_DoC, Connections);
10. *Select the best scenarios (or populations) based on the best values to (DoC).*
    Fig. 11: Pseudo-code for the creation of an Evolutionary Neural Network

If we now submitted to the system the question *Which are the pavements that in the past provided an asphalt structural response with an accuracy of 100%?*, which is expressed in logic terms in the form:

$$\forall(A, B, C, E, V, S, N, H, L)),$$
$$?demo((pavement(A, B, C), climate(D, A, E, F, G),$$
$$asr(E, S, 100, H)), L). \quad (12)$$

we may get:

Once again, and in terms of evolution, are created three new entities, a consequence of the two connections that are established between the extensions of the predicates *pavement* and *climate* and between *climate* and *asr*, which may be expressed in the form:

pavement(0.035, 1, asphalt_concrete_A, 100, 0.77).
climate(0.25, 2, 1, 50, climate_type_2, true, 0.8).
asr(0.25, 50, aStruct_R_type_1, 100, 33, 0.88).

At this stage (i.e., $t=2$), the genome of the virtual intellect will present the form (Fig. 12):

4.5 The genetic operators

4.5.1 Crossover

In Fig. 13, it is depicted the modus operandi of the crossover operator, where *Parent 1* and *Parent 2* denote, respectively, the genomes given in Figs. 9 and 12.

4.5.2 Mutation

In Fig. 14, we present the modus operandi of the mutation operator to a single point.

It is now possible to present the modus operandi that leads to the creation of new knowledge (Fig. 15).

The intellect sub-schemes, in a pictorial form, that may allow one to solve the questions referred to above are given below (Fig. 16).

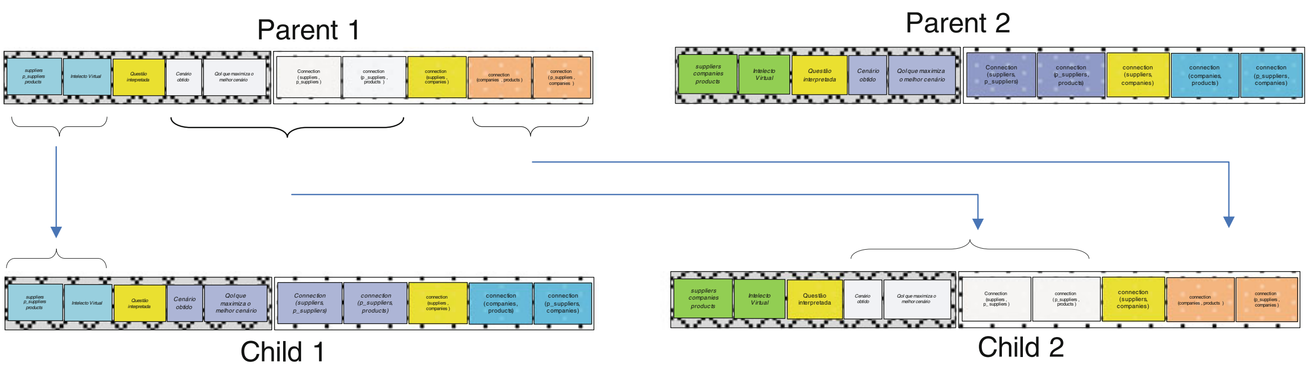


Fig. 13 Modus operandi of the crossover operator

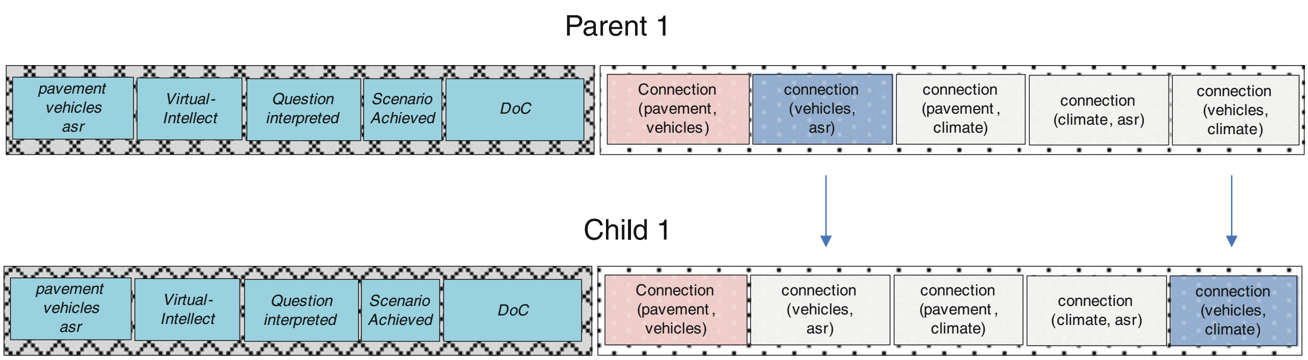


Fig. 14 Modus operandi of the mutation operator

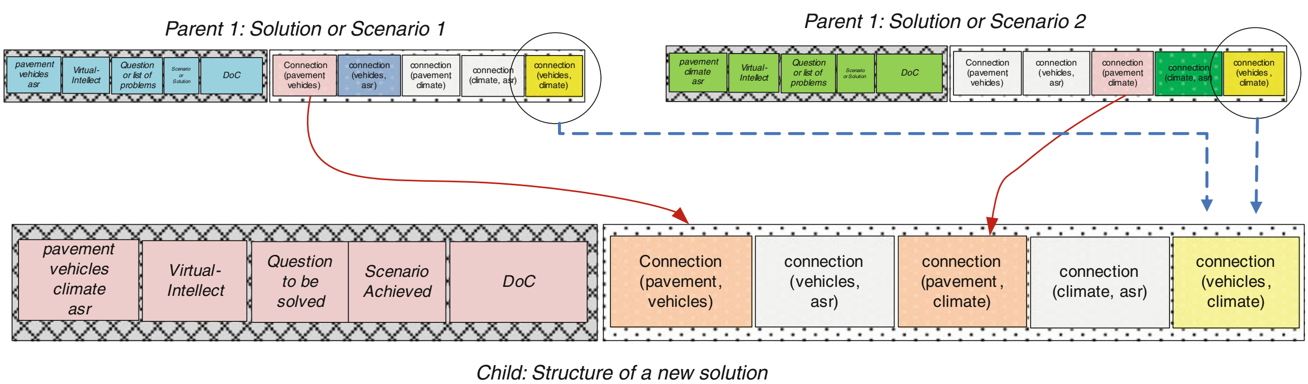


Fig. 15 The modus operandi that leads to the creation of new knowledge

It is now possible to look at the creation of evolving systems in the area of asphalt pavement that may be used as computational tools to assess the asphalt structural response. This is accomplished by presenting the system with questions of the type:

Which are the pavements that may now support an asphalt structural response with an accuracy of 100%?

$$?demo((pavement(V_1, A, B, C, L), (vehicles(V_2, A, D, F, M), F > 0), asr(V_3, D, N, 100, Cr, O)), Truth\_Value).$$

- *Which are the pavements that in the past provided an asphalt structural response with an accuracy of 100%?*

$$?demo((pavement(V_p, X, Y, Z, L), climate(V_2, A, X, P, N, R, M), asr(V_3, P, NP, 100, Cr, O)), Truth\_Value).$$

As a side-effect of invoking the theorem prover *demo*, an intellect scheme is generated, whose evolution is dictated by the scenario under consideration (Fig. 17), which may be depicted in the form [76]:

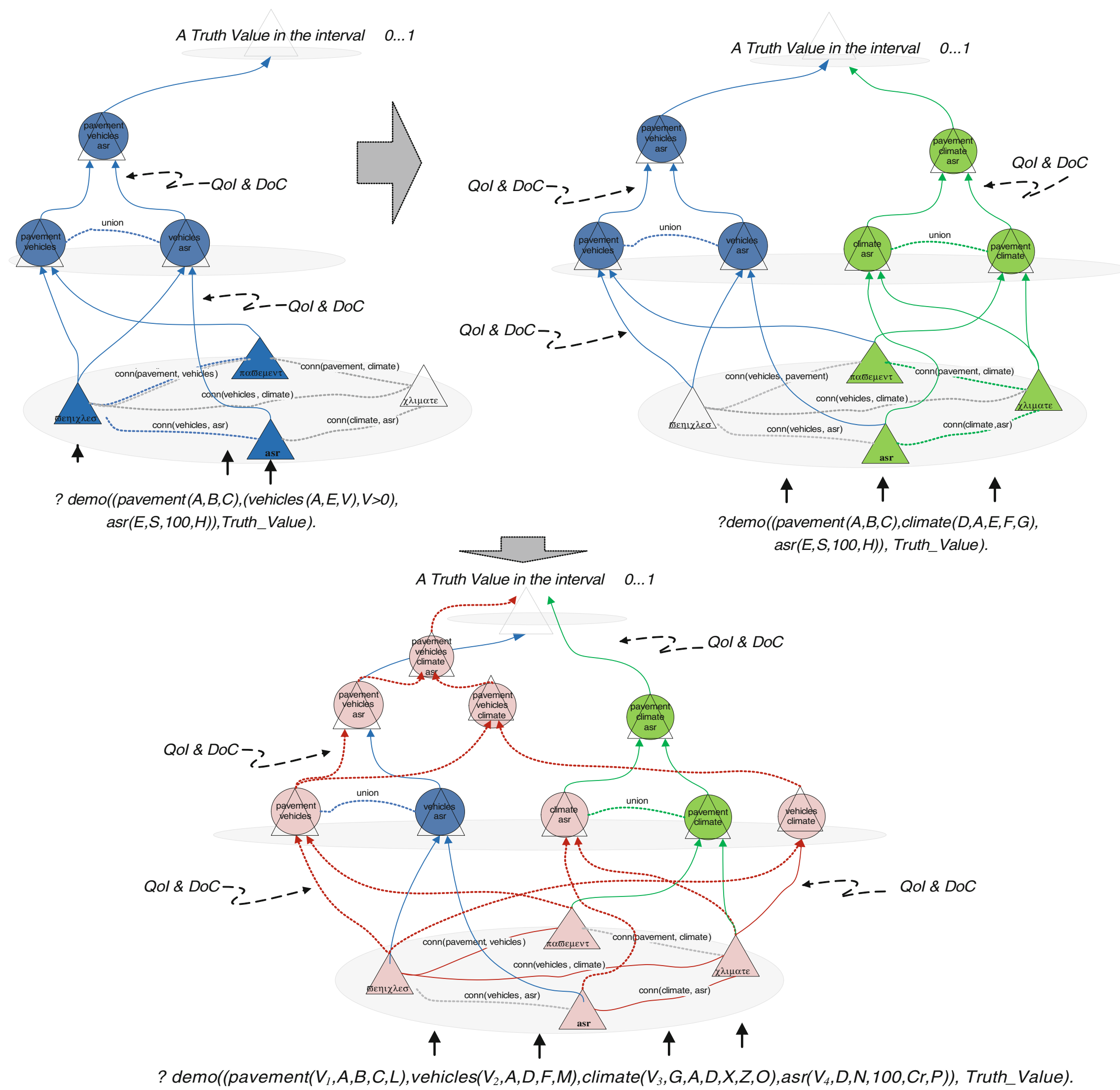


Fig. 16 The process of generation and consolidation of an virtual intellect

```
{
 ¬pavement(V,X,Y,Z,R)← not pavement(V,X,Y,Z,R),
pavement(0.035,1, asphalt_concrete_A, 100, 0.77),
 ...
¬vehicles(V,X,Y,Z,R)← not vehicles(V,X,Y,Z,R),
vehicles(0.25,1,50,11000,0.83),
...
 ¬climate(V,W,X,Y,Z,W,H) ← not climate(V,W,X,Y,Z,W,H),
   climate(0.25,2,1,50,climate_type_2,true,0.8),
...
 ¬asr(V,X,Y,Z,W,R) ← not asr(V,X,Y,Z,W,R),
asr(0.25,50, aStruct_R_type_1,100,33,0.88),
...
}
```

Indeed, this work focuses on the creation of an evolutionary intelligence tool to predict the asphalt structural response in terms of the QoI and our DoC on the attributes of the terms that make the extensions of the predicates that model the universe of discourse. The problems solved using these computational techniques are well defined in terms of the formal framework referred to above. Indeed, using the evolutionary programming paradigm, the candidate solutions are seen as evolutionary logic programs or theories, being the test whether a solution is optimal based on a measure of the *DoC* carried out by those logical theories or programs

5 Conclusions and future work

The empiric computational paradigm used to predict the long-term asphalt structural response remains almost untouched, at an unsustainable level, not providing accurate or acceptable predictions for the twenty-first century challenges.

However, in the past decades, a small but growing number of studies have been made with the use of AI-based

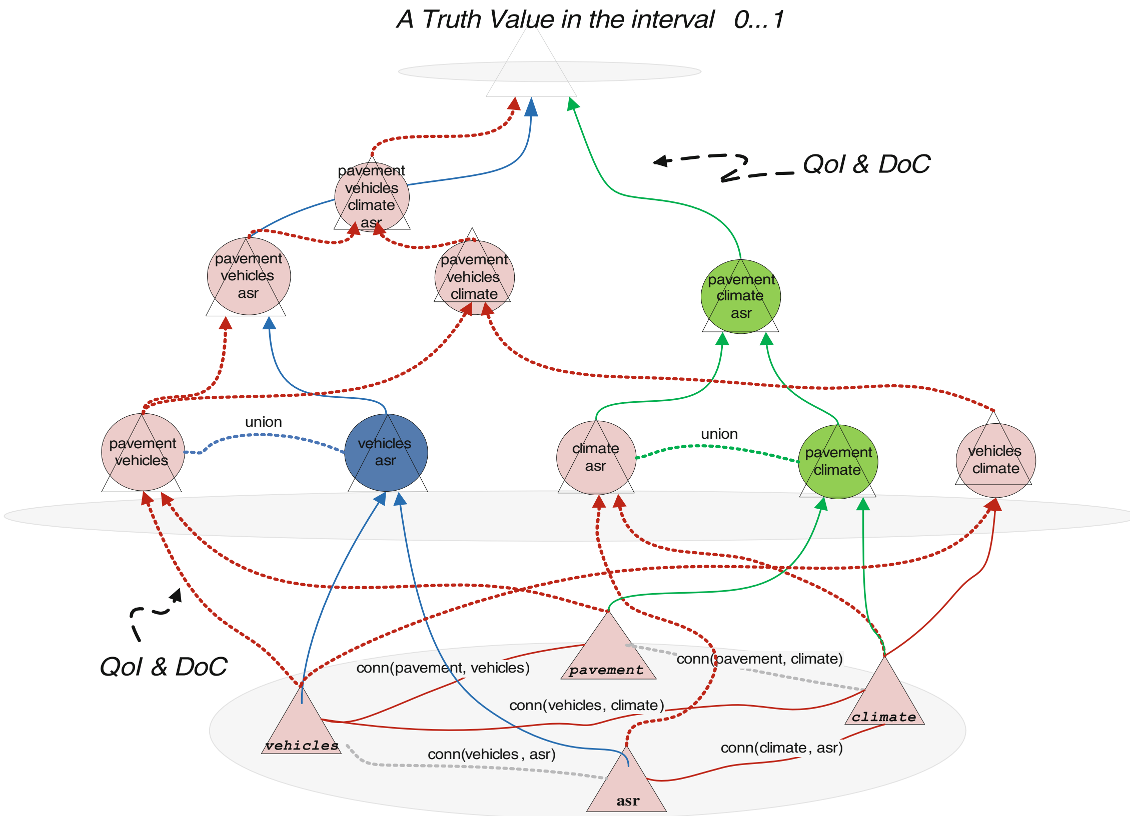


Fig. 17 Auto-organization of the virtual intellect after $t=2$

techniques to understand the asphalt pavements behavior, namely looking at performance prediction, pavement management and evaluation.

In this work we follow this trend, presenting a computational framework based on the symbolic, evolutionary and connectionist paradigms for problem solving, that addresses, in formal terms, the problem of the asphalt structural response. The architecture underlying this evolutionary system is versatile, creative and powerful enough to engender a practically infinite variety of data processing and analysis capabilities, adaptable to any conceivable task in asphalt pavement modeling. In future articles, we will present the full extension of predicate demo, in terms of its functionalities, that will allow us to foresee the emergence of learning, thinking machines, under a symbolic and mathematical approach to computing, presenting also a good opportunity to study the real nature of intelligence.

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References

1. Cook, S., Clark, J.: City of Denton white paper street maintenance and pavement management systems, Denton (2002)
2. Salini, R., Neves, J., Abelha, A.: The road map to apply evolutionary intelligence to asphalt pavement modelling. In: 22nd European conference on modelling and simulation (ECMS 2008). Nicosia, Cyprus (2008)
3. Jansen, J., Schmidt, B.: Performance models and prediction of increase overlay need in Danish state highway performance management system. In: Third international conference on managing pavements, San Antonio, pp. 74–84 (1994)
4. Bandara, N., Gunartne, M.: Current and future pavement maintenance prioritization based on rapid visual condition evaluation. J. Transp. Eng. **127**(2), 116–123 (2001)
5. Zimmerman, K., Botelho, F., Clark, D.: Taking pavement management into the next millennium, Transportation Research Board. A2B01: Committee on Pavement Management Systems (2000)
6. AASHTO, Transportation Asset Management Guide, American Association of State Highway and Transportation Officials. National Cooperative Highway Research Program (NCHRP) (2002)
7. Yang, J., Lu, J.J., Gunaratne, M., Xiang, Q.: Overall pavement condition forecasting using neural networks: application to Florida highway network. In: 82nd annual meeting of the transportation research board (2003)
8. Bosurgi, G., Trifirò, F.: A model based on artificial neural networks and genetic algorithms for pavement maintenance management. Int. J. Pavement **6**(3), 201–209 (2005)
9. Forbus, K.D.: Qualitative reasoning. CRC Handbook of Computer Science and Engineering, pp. 715–733 (1996)
10. Kuipers, B.: Qualitative reasoning: modeling and simulation with incomplete knowledge, MIT press (1994)
11. Bredenhann, S., van de Ven, M.F.C.: Application of artificial neural networks in the back-calculation of flexible pavement layer moduli from deflection measurements. In: Proceedings of

the 8th conference on asphalt pavements for Southern Africa (CAPSA'04), Sun City (2004)
12. Liu, Y., Sun, M.: Fuzzy optimization BP neural network model for pavement performance assessment. In: 2007 IEEE international conference on grey systems and intelligent services, Nanjing, China, pp. 18–20 (2007)
13. Terzi.: Modeling the pavement serviceability ratio of flexible highway pavements by artificial neural networks. Constr. Build. Mater. **21**, 590–593 (2007)
14. Sheridan, F.: A survey of techniques for inference under uncertainty. Artif. Intell. Rev. **5**(1), 89 (1991)
15. Kakas, A., Kowalski, R., Toni, F.: The role of abduction in logic programming. In: Gabbay, D., Hogger, C., Robinson, I. (eds.) Handbook of Logic in Artificial Intelligence and Logic Programming, vol. 5, pp. 235–324. Oxford University Press, Oxford (1998)
16. Kowalski, R.: The logical way to be artificially intelligent. In: Toni, F., Torroni, O. (eds.), Proceedings of the CLIMA VI.LNCS (LNAI), pp. 1–22. Springer, Heidelberg (2006)
17. Neves, J., Machado, J., Analide, C., Abelha, A., Brito, L.: The halt condition in genetic programming. In: Lecture Notes in Artificial Intelligence, vol. 4874. Progress in Artificial Intelligence. Springer, Berlin (2007)
18. Shafer, G.: The Dempster–Shafer theory. Encyclopedia of Artificial Intelligence, 2nd edn. S. C. Shapiro, Wiley (1992)
19. Subrahmanian, V.: Probabilistic databases and logic programming, In: Proc. of the 17th international conference of logic programming (2001)
20. Zadeh, L.A.: Fuzzy logic. The MIT encyclopedia of the cognitive sciences. R.A. Wilson and F.C. Keil, MIT Press (2001)
21. Loyer, Y., Spyratos, N., Stamate, D.: Parametrised semantics for logic programs—a unifying framework. Theor. Comput. Sci. **308**(1–2) (2003)
22. Analide, C., Novais, P., Machado, J., Neves, J.: Quality of knowledge in virtual entities. In: Encyclopedia of Communities of Practice in Information and Knowledge Management. pp. 436–442. Idea Group Inc (2006)
23. Machado, J., Andrade, F., Neves, J., Novais, P., Analide, C.: Formal models in web based contracting. The 2006 IEEE/WIC/ACM international conference on web intelligence and intelligent agent technology (WI-IAT 2006 Workshop Proceedings), Hong Kong, pp. 548–551 (2006)
24. Lima, L., Costa, R., Novais, P., et al.: Quality of information in the context of ambient assisted living. In: Advances in Soft Computing, vol. 50, pp. 624–633. Springer, New York (2008)
25. Machado, J., Miranda, M., Pontes, G., Santos, D., Santos, M., Abelha, A., Neves, J.: Intelligent agents and medical moral dilemmas. In: Proceedings of the 8th WSEAS international conference on applied computer & applied computational science (ACACOS '09), Hangzhou, China (2009)
26. Ribeiro, J., Novais, P., Neves, J., Fernandez-Delgado, M.: Quality of the information: the application in the winification process in wine production. In: Proceedings of the 2009 European Computing Conference of the World Scientific and Engineering Academy and Society, Tbilisi, Georgia, pp. 62–70, ISBN: 978-960-474-088-8 (2009)
27. Lima, L., Novais, P., Bulas Cruz, J.: A process model for group decision making with quality evaluation. In: Omatiu, S., et al. (eds.) Distributed Computing, Artificial Intelligence, Bioinformatics, Soft Computing and Ambient Assisted Living, LNCS 5518, pp. 566–573. Springer, New York (2009)
28. Machado, J., Abelha, A., Novais, P., Neves, J., Neves, J.: Quality of service in healthcare units. Int. J. Comput. Aided Eng. Technol. **2**(4), 436–449 (2010)
29. Novais, P., Salazar, M., Ribeiro, J., Analide, C., Neves, J.: Decision making and quality-of-information. In: Corchado E., Novais P., Analide C., Sedano J., (eds.) Soft Computing Models in Industrial and Environmental Applications, 5th International Workshop (SOCO 2010), Series Advances in Intelligent and Soft Computing, vol. 73, ISBN: 978-3-642-13160-8, pp. 187–195. International Workshop on Soft Computing Models in Industrial Applications. Springer, Guimarães (2010)
30. Novais, P., Andrade, F., Machado, J., Neves, J.: Agents, trust and contracts. In: Portela, I., Cunha, M. (eds.) Information Communication Technology Law, Protection and Access Rights: Global Approaches and Issues. IGI Global (2010)
31. Reus, S., Abelha, A., Neves, J.: INTELLIPave—considering aside failure criteria and unknown variables in evolutionary intelligence based models for asphalt pavement. In: Proceedings of the 23rd European conference on modelling and simulation, pp. 624–629, ISBN: 978-0-9553018-8-9/ISBN: 978-0-9553018-9-6 (CD) (2009)
32. Flintsch, G.W.: Soft computing applications in pavement and infrastructure management: state-of-the-art. Transportation Research Board Annual Meeting (2003)
33. Madanat, S., Prozzi, J.A., Han, M.: Effect of performance model accuracy on optimal pavement design. Comput. Aided Civ. Inf. Eng. **17**, 22–30 (2002)
34. Carey, W., Irick, P.: The pavement serviceability performance concept. Highway Research Board Special Report 61E, AASHO Road Test (1962)
35. Reus, S.: Utilização de Borracha Reciclada de Pneus em Misturas Asfálticas. Tese de Mestrado 138 (2000)
36. AASHTO.: Pavement design guide. Memorandum, American Association of State Highway and Transportation Officials, Frankfort, Kentucky (2004)
37. National Cooperative Highway Research Program: NCHRP 1-37A, Guide for mechanistic–empirical design of new and rehabilitated pavement structures (2004)
38. Tutumluer, E., Seyhan, U.: Neural network modeling of anisotropic aggregate behavior from repeated load triaxial tests. Transportation Research Record 1615, pp. 86–93 (1998)
39. Penumadu, D., Jin-Nan, L., Chameau, J.L., Arumugam, S.: Rate-dependent behavior of clays using neural networks. In: Proceedings of the 13th conference of the international society for soil mechanics and foundation engineering, vol. 4, pp. 1445–1448 (199)
40. Penumadu, D., Zhao, R.: Triaxial compression behavior of sand and gravel using artificial neural networks (ANN). Comput. Geotech. **24**, 207–230 (1999)
41. Basheer, I.A., Najjar, Y.M.: Modeling cyclic constitutive behavior by neural networks: theoretical and real data. In: Proceedings of the 12th engineering mechanics conference, pp. 952–955 (1998)
42. Ellis, W.G., Yao, C., Zhao, R., Penumadu, D.: Stress–strain modeling of sands using artificial neural networks. J. Geotech. Eng. **121**(5), 429–435 (1995)
43. Meier, R.W., Alexander, D.R., Freeman, R.B.: Using artificial neural networks as a forward approach to backcalculation. Transportation Research Record 1570, pp. 126–133 (1997)
44. Halil, C., Guclu, A., Tutumluer, E., Thompson, M.R.: Use of artificial neural networks for backcalculation of pavement layer moduli. 2004 FWD Users Group Meeting 22 (2004)
45. Roberts, A.C., Attoh-Okine, O.N.: Comparative analysis of two artificial neural networks using pavement performance prediction. Comput. Aided Civil Infrastruct. Eng. **13**(5), 339–343 (1998)
46. Faghri, A., Hua, J.: Roadway seasonal classification using neural networks. J. Comput. Civil Eng. **9**(3), 209–215 (1995)
47. Lingras, P.: Classifying highways: hierarchical grouping versus Kohonen neural networks. J. Transp. Eng. **121**(4), 364–368 (1995)

48. Wangxin, X., Yan, X., Zhang, X.: Pavement distress image automatic classification based on DENSITY-based neural network. RSKT 2006, LNAI 4062. pp. 685–692 (2006)
49. Justin, B., Verma , B., Li, X., He, W.: A neural network based technique for automatic classification of road cracks. In: International joint conference on neural networks, vol. 6 (2006)
50. Imad, A., Melchor-Lucero, O., Ferregut, C., Nazarian, S.: Development of a comprehensive, rational method for determination of remaining life of an existing pavement. Research Report 1711-2, The Center for Highway Materials Research, The University of Texas at El Paso, El Paso, Texas, United States of America. Sponsor: Texas Department of Transportation (2000)
51. Miradi, M.: Knowledge discovery and pavement performance—intelligent data mining. Delft University of Technology, Section of Road and Railway Engineering (Ph.D. Thesis), p. 324. ISBN: 978-90-8570-278-8 (2009)
52. Yudong, C.: Soil classification by neural network. Adv. Eng. Softw. **22**, 3 (1995)
53. Bosurgi, G., Trifirò, F.: A model based on artificial neural networks and genetic algorithms for pavement maintenance management. Int. J. Pavement, 201–209 (2005)
54. Bosurgi, G., Trifirò, F., Xibilia, M.G.: Artificial neural networks for predicting road pavement conditions. 4^o INTERNATIONAL SIIV CONGRESS 12 (2007)
55. Venayagamoorthy, V., Allopi, D.: Use of neural network in the prediction of bearing capacity of pavement structure. In: 26th South African transport conference (SATC 2007), vol. 8 (2007)
56. Thube, D.T., Parida, M., Jain, S.S.: Application of artificial neural network (ANN) for prediction of pavement derioration for low volume roads in India. In: 22nd ARRB conference, research into practice, vol. 11 (2006)
57. Onur, P., Tutumluer, E., Thompson, M.: Nondestructive pavement evaluation using ILLI-PAVE based artificial neural network models. Research Report FHWA-ICT-08-022, Illinois Center for Transportation, Illinois (2008)
58. Kasthurirangann, G., Thompson, M.R., Manik, A.: Rapid finite-element based airport pavement moduli solutions using neural networks. Int. J. Comput. Intell. (Winter 2007) (2007)
59. Alessandra, B., Bandin, P.: Prediction of pavement performance through neuro-fuzzy reasoning. Comput. Aided Civil Infrastruct. Eng, 39–54. http://onlinelibrary.wiley.com. doi:10.1111/j.1467-8667.2009.00615.x/full (2010)
60. Taskiran, T.: Prediction of California bearing ratio (CBR) of fine grained soils by AI methods. Adv. Eng. Softw. **41**, 886–892. http://www.elsevier.com/locate/advengsoft (2010)
61. Serkan, T., Çevik, A., Usar, Ü.: Prediction of Marshall test results for polypropylene modified dense bituminous mixtures using neural networks. Expert Syst. Appl. **11** (2010)
62. Mustafa B.B., Teomete, E., Agarwal, M.: Use of artificial neural networks for predicting rigid pavement roughness. Midwest Transportation Consortium (2004)
63. Lisa AH, Jackson E, Dougan, C.E., Choi, S.N.: Models relating pavement quality measures. Transportation Research Record 1869 (2004)
64. Ribeiro, J., Machado, J., Abelha, A., Fernandéz-Delgado, M., Neves, J.: Handling incomplete information in an evolutionary environment. In: Proc. of the WCCI 2010 IEEE world congress on computational intelligence, pp. 2786–2793. CCIB, Barcelona (2010)
65. Pereira, L.M., Lopes, G.: Prospective logic agents. In: Neves, J.M., Santos, M.F., Machado, J.M. (eds.) Progress in Artificial Intelligence. Proc. 13th Portuguese intl. conf. on artificial intelligence, pp. 73–86. Springer LNAI 4784 (2007)
66. Spyratos, L.Y., Stamate, D.: Hypothesis-based semantics of logic programs in multivalued logics. ACM Transactions on Computational Logic (2004)
67. Molina-Garcia, M., Ullman, J., Widom, J.: Database systems the complete book. Prentice Hall (2002)
68. Gelfond, M., Lifschitz, V.: The stable model semantics for logic programming. In: Kowalski, R., Bowen, K. (eds.) Logic programming: Proc. fifth int'l conf. and symp., pp. 1070–1080 (1998)
69. Pereira, L.M., Anh, H.T.: Evolution prospection. In: Nakamatsu, K. (ed.) Procs. first KES intl. symposium on intelligent decision technologies (KES-IDT'09), Himeji, Japan (2009)
70. Neves, J.: A logic interpreter to handle time and negation in logic data bases (1984)
71. Halpern, J.: Reasoning about uncertainty. MIT Press (2005)
72. Kovalerchuck, B., Resconi, G.: Agent-based uncertainty logic network. In: Procs. of the WCCI 2010, IEEE, Barcelona, pp. 596–603 (2010)
73. Lucas, P.: Quality checking of medical guidelines through logical abduction. Proc. of AI-2003 20, pp. 309–321 (2003)
74. Hommerson, A., Lucas, P., van Bommel, P.: Checking the quality of clinical guidelines using automated reasoning tools. Theory Pract. Logic Program. **8**(5–6), 611–641 (2008)
75. Machado, J., Abelha, A., Novais, P., Neves, J., Neves, J.: Quality of service in healthcare units. Int. J. Comput. Aided Eng. Technol. **2**(4), 436–449 (2010)
76. Ribeiro, J.: Evolutivo de Inteligencia em la optimización de funciones. Ph.D Thesis, University of Santiago de Compostela (2011)