Hierarchical IF-Inference Systems for Local Sustainable Development Management

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Abstract: - The paper presents basic notions of IF-sets introduced by K.T. Atanassov and the design of new hierarchical IF-inference systems of Mamdani type for the modelling of decision processes. We propose a tree hierarchical IF-inference system which can serve as a decision support system in the management of local sustainable development. The possibility to model both the uncertainty and the relationships in the complex system of local sustainable development represent the main advantages of this system. It provides stronger possibility to accommodate imprecise information compared to fuzzy inference systems and, at the same time, the number of if-then rules is reduced by using a tree hierarchical structure. The relationships among sustainable development indicators and their weights are incorporated through the expert opinions.

Key-Words: - Intuitionistic sets, IF-sets, hierarchical IF-inference systems, sustainable development, indicators.

1 Introduction

Sustainable development (SD) is generally understood as such a development to ensure the fulfilment of the needs of contemporary society without jeopardizing the opportunity to meet the needs of future generations. As the notion of SD expanded, it became apparent that traditional indicators such as gross domestic product failed to address issues inherent in the sustainability concept, and therefore different measures had to be developed. Sustainable development indicators (SDIs) emerged to fill this gap while after the Rio de Janeiro Summit in 1992 they started to become widespread. The concept of SD is often illustrated in terms of three inter-related dimensions of society, i.e. the social, environmental, and economic dimensions. The aim of SDIs' design is to develop a framework that attempts to bring the economic, social, and environmental aspects of society together, emphasizing the links between them.

The aim of the paper is to discuss the design and the use of the SDIs and the possibilities of their modelling. The paper reviews the current literature and practice with regard to the use of the SDIs for a decision support system (DSS) design. The main challenge of current DSSs used for SD modelling lies in resolving a great deal of uncertainty in environmental and social domains. Therefore, we develop a system for modelling such an uncertainty which is based on IF-sets.

At this time there are several generalizations of fuzzy set theory for various objectives [1], [2]. The theory of IF-sets [3], [4], [5], [6] represents one of the generalizations, the notion introduced by K.T. Atanassov [7], [8]. The IF-sets are for example also suitable for the SD modelling as they provide a good description of object attributes by means of membership functions and non-membership functions. They also present a strong possibility to express uncertainty.

The paper presents the literature review of SD modelling, the design of local SDIs, the basic notions of IF-sets and hierarchical IF-inference systems (IFISs) of Mamdani type. Based on [9], the output of IFIS is defined in general. In the next part of the paper, we design and formalize hierarchical IFIS of Mamdani type for classification of the i-th municipality $o_i \in O$, $O=\{o_1,o_2, \dots ,o_i, \dots ,o_n\}$ into the j-th class $\omega_j \in \Omega$, $\Omega=\{\omega_1,\omega_2, \dots ,\omega_j, \dots ,\omega_p\}$. Using this system, the reduction of if-then rules is achieved. The classification presented in this paper may assist state administration to evaluate local SD. The knowledge of notable experts in the field of SD measuring gives support to the results of the classification.

2 Sustainable Development Modelling

The modelling of SD results from the following purposes: decision-making and management, advocacy, participation and consensus building, and research and analysis. Consequently, there is a need for monitoring actual development over time and for identifying changing conflicts of interest between actors. In general, it would be desirable to construct a comprehensive impact model which would encapsulate the complex interacting patterns of regional development and related land use in relation to social and environmental variables.

Such a modelling activity could take the form of a DSS (linking empirical data and statistical methods with expert knowledge), an optimization model (optimizing economic, social and environmental objectives simultaneously), a simulation model (calibrated at best by plausible information), or a general equilibrium model (validated by empirical data).

2.1 Decision-Support Systems

The SDIs offer support in policy making, they serve as planning tools which help choose among alternative policies. This function of SDIs is crucial when designing a DSS.

A sample of a DSS proposed in [10] aims to propose an approach to consolidating and analyzing spatial information in the context of limited modelling resources. Rooted in practical experience, a method is proposed that combines two multiple criteria decision-making techniques (weighted linear combination and analytical hierarchical processes), parameterized in a participatory process and implemented in a geographical information systems (GISs).

The so called Flag model was introduced by [11] in order to assess the degree of sustainability of various policy alternatives. The model is based on three consequent components, identifying a set of measurable SDIs, establishing a set of normative reference values, and developing a practical impact methodology for assessing future developments.

The need, therefore, is for a decision-making process that can accommodate change in a number of non-equivalent dimensions [12]. This objective is born in mind in the model called Sustainability Assessment Map [12]. This is a tool for representing change on a number of dimensions simultaneously. The Sustainability Assessment Map consists of a diagram in which each of the critical dimensions in a compound problem is represented by an axis. The resultant profiles can be differentiated. For example, the first step can be an identification of the critical axes of change (e.g. costs, profits, numbers of jobs, environmental impacts, etc.). Each of the main development options is then assessed on the same basis and scored on all of the axes concerned. The scores are then differentiated, and the results displayed in the sustainability assessment map.

Further, it is noteworthy that the spatial scale of analysis may be handled by using GIS. Such modern GIS techniques have been instrumental in developing interactive modes between quantitative modelling and spatial mapping [13]. Especially when regional development plans have a bearing on land use (e.g., in relation to agricultural policy aiming at food security, self-reliance or pesticides management), GIS may offer a powerful analytical tool for the modelling of spatial SD.

Cost-benefit analysis represents a traditional decision-support tool. In its simple form, cost-benefit analysis is carried out using only financial costs and financial benefits. For example, a simple cost benefit ratio for a road scheme would measure the cost of building the road, and subtract this from the economic benefit of improving transport links. It would not measure either the cost of environmental damage or the benefit of quicker and easier travel to work. A more sophisticated approach to building a cost benefit models is to try to put a financial value on intangible costs and benefits. However, the subjectivity of the valuation is evident. The sample of using cost-benefit analysis in environmental sustainability is presented by [14].

Another approach reflects the principle of public participation in SD decisions as expressed in the Rio de Janeiro Summit Declaration on Environment and Development. Public and stakeholder participation in the SD decision-making process has increased recently (social responsibility, social learning, etc.) as presented by [15]. Mediated modelling represents a tool for participatory modelling aiming for a collaborative team learning experience to raise the shared level of understanding in a stakeholder group, while foresting a broad level of consensus. Mediated modelling is based on the principles of the methodology of system dynamics. A combination of mediated modelling and multi-criteria assessment in a participatory decision-making context is discussed by [16].

Recent development [17] shows a continuum between integrated assessment modelling and environmental decision-support systems with varying levels of stakeholder participation in both environmental decision-support systems' development and application. There is a general tendency towards better utilization of interdisciplinary data, integration and visualization of temporal and spatial results.

As DSSs point out the clarity of the results presented to their users, the problem is rising with a high number of SDIs. Therefore, many studies aim at the reduction of feature space. As a result, one or several scores are obtained. Principle component analysis is a usual technique applied for this purpose. Environmental Degradation Index [18], and the Index of Globalization [19] represent examples of such models.

However, the DSS approach is considered to have three important problems [12]. First, it resolves a great deal of uncertainty in environmental and social domains in the process of translating and mapping the information. It provides maximum simplicity in the final decision but, at the same time, entails maximum loss of information. So, critically important information may be lost. Second, such an approach will not contribute to any real understanding of the dynamic interaction of complex environmental and economic systems. The third problem concerns the use of information in the real world, and the political issue of the relationship between information and power. Any decision-making procedure using a single index has to assign weights to different factors. Therefore, the choice of methodology for doing so is usually the most important part of the process.

2.2 Sustainable Development Optimization Models

Even though some real world problems can be reduced to a matter of single objective, very often it is hard to define all the aspects in such terms. Defining multiple objectives often gives a better idea of the task. As soon as there are several possibly contradicting objectives to be optimized simultaneously, there is no longer a single optimal solution but rather a whole set of possible solutions of equivalent quality. To obtain the optimal solution, there will be a set of optimal trade-offs between the conflicting objectives. A multi-objective optimization problem is defined by a function which maps a set of constraint variables to a set of objective values. As evident, in a real world situation a decision-making (trade-off) process is required to obtain the optimal solution. Even though there are several ways to approach a multi-objective optimization problem, most work is concentrated on the approximation of the Pareto set [20], [21]. A spatial multi-objective optimization model, which encourages efficient utilization of urban space through infill development, compatibility of adjacent land uses, and defensible redevelopment is proposed by [20]. Another approach presented by [21] relies on the use of shape constraints within the context of discrete multi-objective programming models set on a regular, or uniform grid structure. Several model formulations are presented including a nonlinear discrete optimization model that addresses an explicit districting problem. A heuristic algorithm is developed to generate a solution for this problem, and computational performance of this algorithm is also presented and discussed by [21].

2.3 Simulating Sustainable Development

The example of a simulation model can be presented by the so-called S-model constituting a system approach [22]. The S-model aims to realize two objectives. The first objective is to provide quantitative indicators to measure and describe the expected regional SD considering the complex interactions within a single region and between the region and its environment. The second objective concerns the applicability of the model for a variety of regions enabling a comparison of the sustainability position between European regions. Starting from any hierarchical thematic framework that is also determined by policy targets and priorities, the indicators, initially designed to be applied at regional scale, aims to interpret and to understand indicators and trends in connection with the regional sustainability system behind [12]. A system approach provides a multidimensional framework in which information from different disciplines and domain can be integrated. This approach entails considering various agents interacting in the real world as systems [12]. Consequently, the real world is considered to be a complex system containing complex subsystems (e.g. environmental, social, and economic systems). These subsystems are open systems interacting with each other, and, at the same time, with many other systems. The policy regulating the behaviour of systems should bear in mind these interactions. It is unlikely that any simple models will be able to capture the behaviour of the mentioned systems.

In [23] it is described how an engineering approach, drawing on mathematical models of systems and processes, contributes to new methods that support decision-making at all levels from strategy and planning to tactics and real-time control. The ability to describe the system or process by a simple and robust mathematical model is critical, and the outputs range from guidance to policy makers on strategic decisions relating to land use, through intelligent decision-support to farmers and on to real-time engineering control of specific processes. Another simulation approach is based on an agent-based system. In [24] it is demonstrated that the integration of cellular automata and agent-based modelling can provide a spatial exploratory tool for generating alternative development patterns. Sustainable development strategies are embedded in the modelling to regulate agents' behaviours. A model was developed by [25] for rational SD in Vilnius (Lithuania) with a special emphasis on pollution by undertaking a complex analysis of micro, meso, and macro environmental factors that affect it. Air pollution models represent samples of complex environmental systems. Another simulation approach consists in the use of artificial intelligence domain, qualitative reasoning [26]. The reason for the modelling SD by qualitative reasoning lies in the evident impact of external factors on the behaviour of the system. Moreover, the factors are usually dynamic and may change during the simulation. An example of such a model making it possible to bridge stated problems is presented by [26].

2.4 General Equilibrium Models

The general equilibrium models (GEM) [27] build upon general equilibrium theory that combines behavioural assumptions on rational economic agents with the analysis of equilibrium conditions. They provide counterfactual (ex-ante) comparisons, assessing the outcomes with reform in place with what would have happened had it not been undertaken (or undertaken in a different way). The simultaneous explanation of the origin and spending of the agents' income makes it possible to address both economy-wide efficiency as well as distributional impacts of policy interference. This has made GEM a standard tool for the quantitative analysis of policy interference in many domains including fiscal policy, trade policy, and environmental policy [27].

The use of quantitative models for measuring SD impacts of policy reforms requires the specification of indicators, instruments, and analytical chains [27]. The central steps involved in constructing and using the GEM for policy impact analysis are summarized as follows [27]. Initially, the policy issue must be carefully studied to decide on the appropriate model design as well as the required data. The second step involves the use of economic theory in order to determine the results in the more complex numerical model (causal chain). In determining results of policy simulations, the choice and parameterization of functional forms are crucial. It requires a consistent data, mostly one year's data (or a single observation represented as an average over a number of years), together with exogenous elasticity that are usually taken from literature surveys. Within the policy simulations single parameters or exogenous variables are changed and a new (counterfactual) equilibrium is computed. Finally, the model results must be interpreted based on sound economic theory.

2.5 Other Approaches

In light of the near-impossibility to construct a development plan or project a dedicated model for each individual regional, in practice one often resorts to an ad hoc impact assessment, based on simple cause-effect relationships. Such a more limited approach has obviously several shortcomings but, at the same time, it is manageable, practical, and based on local expertise. In such a case, foreseeable consequences of various types of human or government intervention can be assessed by a combination of ad hoc surveys, comparative studies, simple correlation techniques [28], local experts' views, and Delphi methods [29].

The uncertainties involved may then be gauged by exercising a systematic sensitivity analysis in a broad range of uncertainty intervals around the information used. According to [29], there are four ways to quantify the effect of SD policies and measures on development and emissions: case studies, national energy modelling, the analysis of sector data, inclusion of policies in global emission allocation models, and input-output models. Case studies as a method illustrate both the local SD benefits and the climate co-benefits of nationally specific actions. Case studies, by their nature, are rooted in national circumstances. They can be used in any country. However, results from case studies are not always easily comparable, since the underlying assumptions and the results reported may not be consistent across studies. Guidelines might be needed for basic parameters that should be reported in case studies. The second methodology considered is to use national energy models to investigate the local SD and climate implications of energy policies. As a method, national energy modelling allows a range of policies and measures in the energy sector to be analyzed together. With an appropriate model choice, the dynamics of the energy system are taken into account. Clearly, the energy modelling method is appropriate only for the energy sector. It would be most useful in those developing countries whose greenhouse gas emissions derive mainly from the energy sector. With the analysis of sector data, the emission reduction potential of a country can be assessed on an aggregated scale to understand the order of the magnitude of reductions that could be achieved with policies and measures, being motivated by SD or by climate change goals. Sector data analysis as a method has the advantage of comparability across countries, but compromises on country-specific details. Scenarios for the future can be developed although, by definition, for sectors rather than the whole economy. The fourth method is represented by global emission allocation models. Models such as the Framework to Assess International Regimes model [30], and Evolution of Commitments model [31] are designed to allocate a given global greenhouse gas emissions budget across countries under different multilateral agreements. These analyses place the SD policies and measures' approach in the context of multi-stage approaches. Such approaches are based on participation and differentiation rules that come into play when a country moves from one stage to another.

The input-output approach is an essential component in environmental analysis, as it enables the determination of direct and indirect sources of pollution by linking data on emissions in physical terms to the input-output tables. The pollution content of final demand can then be calculated. Input-output tables with environment-related extensions are a major component of the basic framework for satellite accounting of the environment. The Leontief input-output model proposed by [28] uses the satellite accounts, and defines output of each product in terms of the amounts used by other producers and the amounts sold to final uses. This defines a set of structural equations which express the input-output relations in terms of the entries in the table or matrix.

3 Design of Sustainable Development Indicators for Czech Municipalities

As stated in Agenda 21, there is a need for acknowledging the importance of sustainability indicators by both national governments and the international organizations which should be followed by the identification of relevant indicators.

The European Commission, among others, uses four capitals (manufactured, natural, human, and social capital) in order to describe SD. When the social, environmental, and economic aspects of society are viewed as separate there is a risk that the problems identified within each sphere are handled in an isolated manner. The need to follow these three dimensions (four capitals) is therefore crucial when designing SDIs. The aim SDIs' design is to develop a framework that attempts to bring the economic, social, and environmental aspects of society together, emphasizing the links between them.

The SDI can generally be understood as a quantitative measure that points to a condition or analyses changes, while measuring and communicating progress towards the stated goals of SD and management of economic, social, institutional, and environmental resources. In particular, SDIs notify of the state of the environment, the economy, and the society, as well as of the weaknesses and potential problems. They also serve as performance assessment tools [32]. Their purpose is to show how well a system is working towards the defined goals. An indicator can also be used in an evaluation, assessing whether a development project takes into consideration the aspects of SD. Therefore, it helps the public, decision makers, and managers to assess the consequences of the decision taken. As a result it could be argued that indicators offer support in policy making; they serve as planning tools which help choose among alternative policies [32].

Additionally, the SDIs help to clarify objectives and to set priorities. They represent explanatory tools which contribute to the translation of the sustainability concept into practical terms [32]. They also help identify data gaps and establish a conceptual framework for data collection [33]. Ideally, the SDIs provide the link between the different components of sustainability reflecting the significance of the dynamics developed in a complex system more than a report of each component separately. Indicators provide meaning beyond the value of the parameter. As a result, evaluation as well as communication of important parameters become instant and easy to understand. Another advantage emanating form the use of indicators is the reproducibility and comparability of the results. If the SDIs are based on a coherent methodology then, they could be used to make comparisons over time and across space, find correlations, and monitor changes and trends [33].

However, there are also problems which could appear while choosing and using indicators. One major difficulty lies in the subjectivity of the selection of the representative SDIs, and the evaluation of the results [33]. The selection of the SDIs is realized by experts with limited knowledge which is referred-to as dependence on a false model [34]. Certain scientific and social background, and therefore certain degree of subjectivity is inevitable [35]. Other problems include lack of appropriate data which may result in missing vital information, and over aggregation of too many things resulting in unclear meaning, and therefore bad communication and analysis capability [34]. If indicators are not chosen carefully and as systematically as possible they will carry a wrong message resulting in misleading conclusions.

The recent trends emphasize the central role of SDI at regional and local level. Agenda 21 called for coordinated efforts to develop SDIs at local, regional, national and global levels. In response, the United Nations Commission on Sustainable Development launched a program to develop indicators of SD in 1995. Five years later, highly aggregated indicators were completed and applied in many countries. Currently there are many SD initiatives at international, national, regional, and local level. The SDIs defined by these initiatives reflect the objectives and specific conditions of the organizations involved.

During the process of economic development, urbanization is unavoidable, which makes cities play an important role in overall economic and social development. In the process of urbanization, although development is fast but without taking SD into consideration, economy development and material centralization will cause problems to environment and social equilibrium [36]. Crises and disasters like environmental pollution, resources scarcity, and species extinction provoke discussions on environmental resources and urban SD. There should be clear cognition to the role of city during the exploration process of SD. It is now widely recognized that cities make an important contribution to social and economic development at national and local levels. According to the United Nations, cities are important engines of economic growth, and absorb two-thirds of the population growth in developing countries. They also offer significant economies of scale in the provision of jobs, housing and services. Thus, they are important centres of productivity and social advancement.

Economic development is necessary, especially for cities in the developing countries [37]. However, sustainable cities should be based on social and economic developments. Urban SD should face issues such as the efficiency of limited resource uses and social justice. In the previous experience, the solution of urban development issues not only relied on the central government, but also local forces and resource inputs played important role, including management of local public and private sectors and communities. Under the framework of the inevitable discussion on economic growth, provided methods to build sustainable community can be described with the characteristics of sustainable community as follows:

- Emphasizing the balance relationship between humans and nature, and consider the limits of environmental carrying capacity;
- Emphasizing the key to community growth is based on the development of community members and the mutual help among communities;
- Emphasizing the establishment of the human environment that has good interaction;
- Keeping the characteristics of cultural diversity.

A sustainable community should be equipped with the following functions [38] having:

- Through technical training, self-growth, and community activities to acquire knowledge;
- Equitable and fair opportunities;
- Including diversified local structures;
- Participating in decision processes and consultations;
- The opportunity of economic development;
- Communities should recognize the needs among different members and try to meet these needs;
- Environmental cognition and responsibility;
- Feeling safe;
- Community identity and sense of belonging;
- Healthy consciousness (construction of an open space).

Consequently, during the assessment process of community sustainability, a valuation system should be built through above-mentioned basic principles. Among those, sustainability indicators systems are the most often used tool. It is addressed in the Local Sustainable Development Indicators that community sustainability indicators should have the following characteristics [39]: building indicators guidelines; planning the implementation mechanism; and developing citizen participation.

To generate community indicators, the process should be realized through long-term communication and adjustments among residents, public departments, expertise, and related parties. The selection and evaluation of indicators should emphasize participatory processes. The participants should be the overall community residents and local departments of the government. The purpose is to provide residents views of community sustainability, to raise awareness, to change individual behaviour or community activities through the participatory process.

Consequently, during the assessment process of community sustainability, a valuation system should be built through above-mentioned basic principles (measurability and comparability). Among those, SDIs systems are the most often used tool. This function of SDIs is crucial when designing a DSS.

Based on the presented principles, the group of experts chose 28 SDIs for the set of Czech municipalities (business activity, investment rate, indebtedness, quality of soil and water, ecological stability, unemployment rate, migration, longevity, etc.). They are shown in Table 1.

Table 1 Design of SDIs for Czech municipalities

	Economic
x_1	Debt per capita
x_2	Operating surplus
x_3	Own revenue/total revenue
x_4	Received grants per capita
x_5	Assets per capita
x_6	Revenue per capita
x_7	Economic active population
x_8	Enterprises per 1000 inhabitants
x_9	Concentration of economy
x_{10}	Average salary
	Environmental
x_{11}	Arable land per capita
x_{12}	Grass stand per capita
x_{13}	Water area per capita
x_{14}	Cross timber per capita
x_{15}	Sewerage
x_{16}	Sewerage plant
x_{17}	Household waste
x_{18}	Coefficient of ecological stability
	Social
x_{19}	Flats per capita
x_{20}	Recreational buildings
x_{21}	Natural growth increment
x_{22}	Balance of migration
x_{23}	Old-age index
x_{24}	Longevity
x_{25}	Employees coming in/out
x_{26}	Unemployment rate
x_{27}	Population
x_{28}	Population with university education

4 IF-Sets and Hierarchical IF-Inference Systems

The concept of IF-sets is the generalization of the concept of fuzzy sets, the notion introduced by L.A. Zadeh [40]. The theory of IF-sets is well suited to deal with vagueness. Recently, the IF-sets have been used to intuitionistic classification models which can accommodate imprecise information [41].

Let a set X be a non-empty fixed set. An IF-set A in X is an object having the form [7], [8]

$$A = \{ \langle x, \mu_A(x), \nu_A(x) \rangle \mid x \in X \}, \qquad (1)$$

where the function μ_A:X→ [0,1] defines the degree of membership function and the function ν_A:X→ [0,1] defines the degree of non-membership function, respectively, of the element x∈X to the set A, which is a subset of X, and A⊂X, respectively; moreover for every x∈X, $0 \le \mu_A(x) + \nu_A(x) \le 1$, ∀x∈X must hold.

The amount $\pi_A(x) = 1 - (\mu_A(x) + \nu_A(x))$ is called the hesitation part, which may cater to either membership value or non-membership value, or both. For each intuitionistic fuzzy set in X, we will call $\pi_A(x) = 1 - (\mu_A(x) + \nu_A(x))$ as the intuitionistic index of the element x in set A. It is a hesitancy degree of x to A. It is obvious that $0 \le \pi_A(x) \le 1$ for each x∈X. The intuitionistic indices $\pi_A(x)$ are such that the larger $\pi_A(x)$ the higher a hesitation margin of the decision maker.

If A and B are two IF-sets of the set X, then [7], [8]

$$
\begin{aligned}
&A\cap B = \{\langle x, \min(\mu_A(x), \mu_B(x)), \max(\nu_A(x),\nu_B(x))\rangle \mid x\in X\},\\
&A\cup B = \{\langle x, \max(\mu_A(x), \mu_B(x)), \min(\nu_A(x),\nu_B(x))\rangle \mid x\in X\},\\
&A\subset B \text{ iff } \forall x\in X, (\mu_A(x) \le \mu_B(x)) \text{ and } (\nu_A(x) \ge \nu_B(x)),\\
&A\supset B \text{ iff } B\subset A, \qquad (2)\\
&A=B \text{ iff } \forall x\in X, (\mu_A(x) = \mu_B(x) \text{ and } \nu_A(x) = \nu_B(x)),\\
&\overline{A}=\{\langle x, \nu_A(x), \mu_A(x)\rangle \mid x\in X\}.
\end{aligned}
$$

Let there exists a general IFIS defined in [9]. Then it is possible to define its output y_η as

$$y_\eta = (1- \pi_A(x)) \times y_\mu + \pi_A(x) \times y_\nu, \qquad (3)$$

where y_μ is the output of the fuzzy inference system (FIS) using the membership function $\mu_A(x)$, y_ν is the output of the FIS using the non-membership function $\nu_A(x)$.

Let there exist the FIS of Mamdani type defined in [42], [43]. Then the number of if-then rules $p_{FIS}=k^m$, where k is the number of membership functions, m is the number of input variables. For a great number m of input variables, the FIS of Mamdani type may be inefficient due to the increase in the number p_{FIS} of if-then rules. One of the ways to reduce the number p_{FIS} of if-then rules is to design the FIS of Mamdani type with a hierarchical structure. The aim of hierarchical FIS design is to reach efficiency and ability to interpret (i.e. with small number p_{FIS} of if-then rules with small number of variables m, and with a small number k of membership functions for each variable). Reducing the number p_{FIS} of if-then rules leads to a reduction in computing demand of the system. This way, it comes to be more effective [42], [43], [44], [45]. Evidently, the same facts hold also for the IFIS of Mamdani type.

Let $x_1,x_2, \dots ,x_k, \dots ,x_m$ be input variables, and let $y_\eta^{1,1}, y_\eta^{1,2}, \dots, y_\eta^{q,1}$ be the outputs of subsystems $IFIS_\eta^{1,1}, IFIS_\eta^{1,2}, \dots, IFIS_\eta^{q,1}$, where η=μ are membership functions (η=ν are non-membership functions). Then, if-then rules $R^{h_{1,1}}, R^{h_{1,2}}, \dots, R^{h_{q,1}}$ of the tree hierarchical IFIS [41], [46], presented in Fig. 1, where q is the number of layers, can be defined as follows:

$$
\begin{aligned}
&IFIS_\eta^{1,1} : R^{h_{1,1}} : \text{if } x_1 \text{ is } A_1^{h_{1,1}} \text{ AND } x_2 \text{ is } A_2^{h_{1,1}}\\
&\qquad \text{then } y_\eta^{1,1} \text{ is } B^{h_{1,1}},\\
&IFIS_\eta^{1,2} : R^{h_{1,2}} : \text{if } x_3 \text{ is } A_3^{h_{1,2}} \text{ AND } x_4 \text{ is } A_4^{h_{1,2}}\\
&\qquad \text{then } y_\eta^{1,2} \text{ is } B^{h_{1,2}},\\
&\qquad \dots, \qquad (4)\\
&IFIS_\eta^{q,1} : R^{h_{q,1}} : \text{if } y_\eta^{q-1,1} \text{ is } B^{h_{q-1,1}} \text{ AND } y_\eta^{q-1,2} \text{ is } B^{h_{q-1,2}}\\
&\qquad \text{then } y_\eta^{q,1} \text{ is } B^{h_{q,1}},
\end{aligned}
$$

where:

– $h_{1,1} = h_{1,2} = \dots = h_{q,u} = \{1,2, \dots ,k^m\}$, u=1,2,

– $A_1^{h_{1,1}}, A_2^{h_{1,1}}, \dots, A_n^{h_{q,1}}$ are linguistic variables corresponding to IF-sets represented as $\eta_1^{h_{1,1}}(x_i), \eta_2^{h_{1,1}}(x_i), \dots, \eta_m^{h_{q,1}}(x)$,

– $B^{h_{1,1}}, B^{h_{1,2}}, \dots, B^{h_{q,1}}$ are linguistic variables corresponding to IF-sets represented as $\eta^{h_{1,1}}(y_\eta^{1,1}), \eta^{h_{1,2}}(y_\eta^{1,2}), \dots, \eta^{h_{q,1}}(y_\eta^{q,1})$,

– $\eta_{B^{h_{1,1}}}(y_j^{1,1}), \eta_{B^{h_{1,2}}}(y_j^{1,2}), \dots, \eta_{B^{h_{q,1}}}(y_j^{q,1})$ are membership function η=μ (non-membership function η=ν) values of aggregate IF-set for outputs $y_j^{1,1}, y_j^{1,2}, \dots, y_j^{q,1}$.

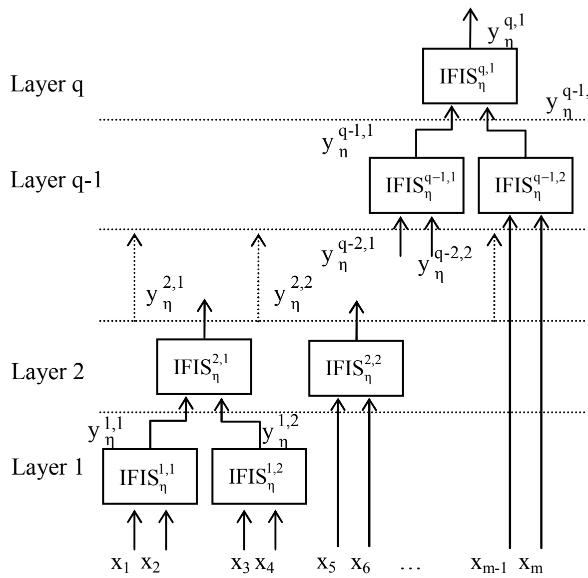

Fig. 1 A tree hierarchical IF-inference system

The outputs $y_\eta^{1,1}, y_\eta^{1,2}, \dots, y_\eta^{q,1}$ of particular subsystems $IFIS_\eta^{1,1}, IFIS_\eta^{1,2}, \dots, IFIS_\eta^{q,1}$ of the tree hierarchical IFIS can be expressed by using defuzzification method Center of Gravity (COG) [42], [43] as

$$y_\eta^{1,1}(B^{h_{1,1}}) = \frac{\sum_{j=1}^{q} y_j^{1,1} \times \eta_{B^{h_{1,1}}}(y_j^{1,1})}{\sum_{j=1}^{q} \eta_{B^{h_{1,1}}}(y_j^{1,1})}, \dots ,$$

$$y_\eta^{q,1}(B^{h_{q,1}}) = \frac{\sum_{j=1}^{q} y_j^{q,1} \times \eta_{B^{h_{q,1}}}(y_j^{q,1})}{\sum_{j=1}^{q} \eta_{B^{h_{q,1}}}(y_j^{q,1})}, \qquad (5)$$

and the outputs of particular subsystems $IFIS_\eta^{1,1}, IFIS_\eta^{1,2}$, … , $IFIS_\eta^{q,1}$ in each layer of the hierarchical IFIS are calculated as follows

$$y_\eta^{r,s}(B^{h_{r,s}})=(1-\pi_\mu^{r,s}) \times y_\mu^{r,s}(B^{h_{r,s}}) + \pi_\nu^{r,s} \times y_\nu^{r,s}(B^{h_{r,s}}),$$
$$\text{for } r = 1,2, \dots ,q,\ s = 1,2. \qquad (6)$$

Similarly, it is possible to design and define a cascade and various others, hybrid hierarchical IFISs.

5 Modelling and Analysis of the Results

Modelling of the local SD is realized by three separate tree hierarchical IFISs for each area of SD (economic, environmental, and social) with inputs parameters $x_1,x_2, \dots ,x_k, \dots ,x_m$, m={10, 8, 10}, outputs $y_\eta^{1,1}, y_\eta^{1,2}, \dots , y_\eta^{q,1}$ of individual subsystems $IFIS_\eta^{1,1}, IFIS_\eta^{1,2}, \dots , IFIS_\eta^{q,1}$, q={5, 4, 5}, see Fig. 2, Fig. 3, and Fig. 4.

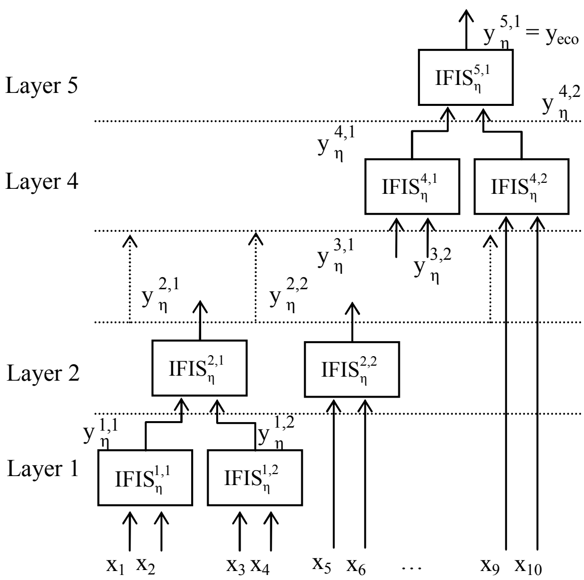

Fig. 2 A tree hierarchical IFIS for economic area

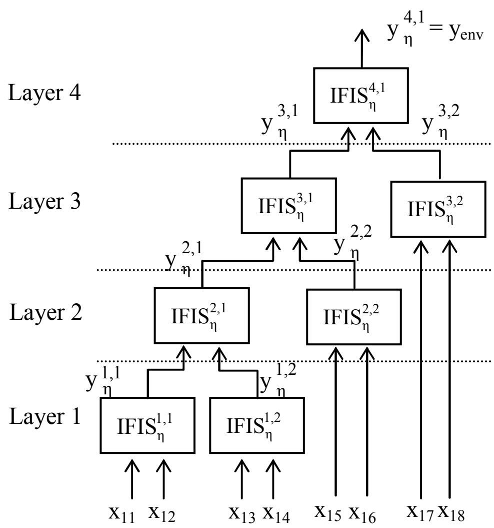

Fig. 3 A tree hierarchical IFIS for environmental area

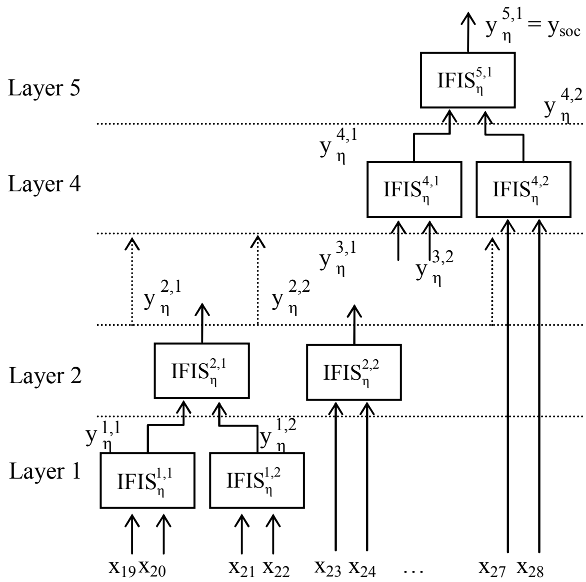

Fig. 4 A tree hierarchical IFIS for social area

The design of specific tree hierarchical IFISs results from the recommendation of experts in the given fields. Thus, it simulates their decision-making process. The design of input (output) membership functions μ and non-membership functions ν is realized by means of c-means clustering algorithm. As an example, the input (output) membership functions μ for input parameter x_1 of the particular subsystem $IFIS_\mu^{1,1}$ are presented in Fig. 5. In a similar manner, the input (output) non-membership functions ν for input the parameter x_1 of the subsystem $IFIS_\nu^{1,1}$ are presented in Fig. 6. These functions are designed for an example of intuitionistic index π=0.05.

The if-then rules of the subsystems $IFIS_\eta^{1,1}, IFIS_\eta^{1,2}$, … , $IFIS_\eta^{q,1}$ are defined by the experts as well. The example of these if-then rules for the subsystem $IFIS_\nu^{1,1}$ is as follows:

for $\eta=\mu$

R^1: if x_1 is lv_x_1 AND x_2 is lv_x_2 then $y_\mu^{1,1}$ is lv_ $y_\mu^{1,1}$,

R^2: if x_1 is lv_x_1 AND x_2 is hv_x_2 then $y_\mu^{1,1}$ is lv_ $y_\mu^{1,1}$,

R^3: if x_1 is hv_x_1 AND x_2 is lv_x_2 then $y_\mu^{1,1}$ is hv_ $y_\mu^{1,1}$,

R^4: if x_1 is hv_x_1 AND x_2 is hv_x_2 then $y_\mu^{1,1}$ is hv_ $y_\mu^{1,1}$.

for $\eta=\nu$

R^1: if x_1 is n_lv_x_1 AND x_2 is n_lv_x_2
then $y_\nu^{1,1}$ is n_lv_ $y_\nu^{1,1}$,

R^2: if x_1 is n_lv_x_1 AND x_2 is n_hv_x_2
then $y_\nu^{1,1}$ is n_lv_ $y_\nu^{1,1}$,

R^3: if x_1 is n_hv_x_1 AND x_2 is n_lv_x_2
then $y_\nu^{1,1}$ is n_hv_ $y_\nu^{1,1}$,

R^4: if x_1 is n_hv_x_1 AND x_2 is n_hv_x_2
then $y_\nu^{1,1}$ is n_hv_ $y_\nu^{1,1}$,

where lv denotes a low value, hv stands for a high value, n_lv is a not low value, and n_hv is a not high value of an input (output).

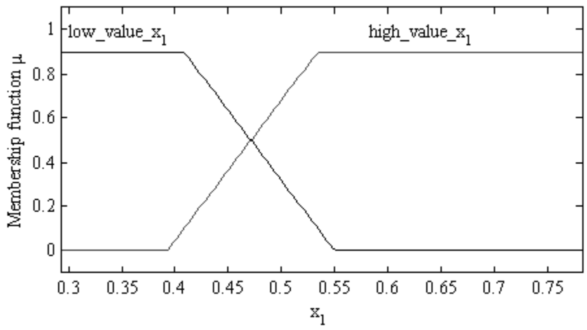

Fig. 5 Input membership functions μ for x_1 of subsystem $IFIS_\mu^{1,1}$

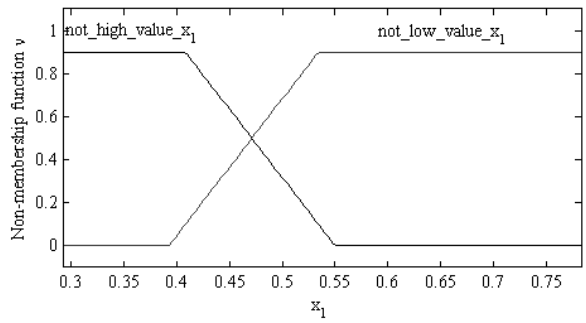

Fig. 6 Input non-membership functions ν for x_1 of subsystem $IFIS_\nu^{1,1}$

The inference mechanism of particular subsystems $IFIS_\eta^{1,1}, IFIS_\eta^{1,2}, \dots, IFIS_\eta^{q,1}$ involves also the process of implication (MIN method) and aggregation (MAX method) within if-then rules, and the process of defuzzification by COG method of obtained outputs to the crisp values. Data for 452 municipalities (Czech Republic) from the year 2006 was used for the modelling of local SD. The designed tree hierarchical IFISs classified objects $o_i \in O$ into three classes ω_1 (low SD), ω_2 (medium SD), and ω_3 (high SD) which considers also the recommendation of experts. The outputs $y_\eta^{q,1} = \{y_{eco}, y_{env}, y_{soc}\}$ of the designed tree hierarchical IFISs for individual SD areas are used as the inputs of a general IFIS resulting in the total SDI represented again by three classes ω_1, ω_2, and ω_3. The total SDI is determined based on the following if-then rules:

for $\eta=\mu$

R^1: if y_{eco} is lv_y_{eco} AND y_{env} is lv_y_{env} AND y_{soc} is lv_y_{soc} then ω_1,

R^2: if y_{eco} is mv_y_{eco} AND y_{env} is lv_y_{env} AND y_{soc} is lv_y_{soc} then ω_1, ... ,

R^9: if y_{eco} is hv_y_{eco} AND y_{env} is hv_y_{env} AND y_{soc} is hv_y_{soc} then ω_3.

for $\eta=\nu$

R^1: if y_{eco} is n_lv_y_{eco} AND y_{env} is n_lv_y_{env} AND y_{soc} is n_lv_y_{soc} then n_ω_1,

R^2: if y_{eco} is n_mv_y_{eco} AND y_{env} is n_lv_y_{env} AND y_{soc} is n_lv_y_{soc} then n_ω_1, ... ,

R^9: if y_{eco} is n_hv_y_{eco} AND y_{env} is n_hv_y_{env} AND y_{soc} is n_hv_y_{soc} then n_ω_3.

where mv denotes a medium value and n_mv is a not medium value. By means of intuitionistic index π it is possible to calculate association index ξ. Association index $\xi=\mu-\nu\times\pi$ [47] emphasizes high values of the membership function μ (association) and reduces low values of the non-membership function ν (non-association). Based on the analysis of the association index ξ it is possible to classify the i-th municipality $o_i \in O$ into the j-th class $\omega_j \in \Omega$, j=1,2,3 in the region of Pardubice, the Czech Republic. The frequencies f of the classes $\omega_j \in \Omega$ are presented in Fig. 7.

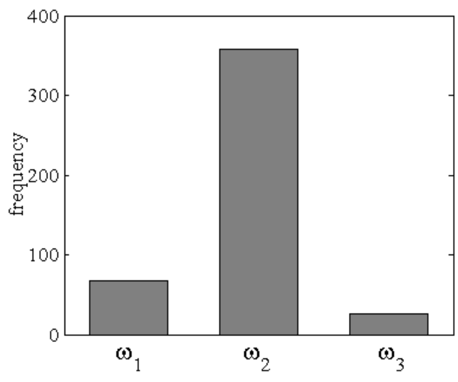

Fig. 7 The frequencies f of the classes $\omega_j \in \Omega$

In Table 2 membership functions μ and non-membership functions ν (to classes $\omega_j \in \Omega$) are assigned to each municipality $o_i \in O$, where intuitionistic index π=0.05.

Table 2 Membership functions μ and non-membership functions ν (to classes $\omega_j \in \Omega$) assigned to a sample of municipalities, π=0.05

Municipality	ω_1		ω_2		ω_3	
	μ	ν	μ	ν	μ	ν
Benatky	0.51	0.44	0.49	0.46	0.05	0.90
Biskupice	0.33	0.62	0.67	0.28	0.05	0.90
Bukovka	0.95	0.00	0.05	0.90	0.05	0.90
…	…	…	…	…	…	…
Volec	0.05	0.90	0.95	0.00	0.05	0.90
Zderaz	0.30	0.65	0.70	0.25	0.05	0.90
Zamberk	0.05	0.90	0.95	0.00	0.05	0.90

6 Conclusion

The modelling of SD is currently realized by optimization models, simulation models, general equilibrium models, or by DSSs. The use of DSSs is based on the idea that relevant, measurable and comparable SDIs are at disposal. However, the DSS approach is considered to have three important problems (high uncertainty in the process of translating and mapping the SDIs; the dynamic interaction of complex economic, environmental and social systems is not embodied; when using a single index weights have to be assigned to different factors).

The IF-sets theory has been applied in different areas, for example in classification and prediction [41], [48], [49], [50], [51]. IF-sets are, for example, also suitable for local sustainable development modelling as they provide a good description of object attributes by means of membership functions and non-membership functions. They also present a strong possibility to express uncertainty.

Therefore, the models based on IF-sets are designed in this paper as they allow processing uncertainty and the expert knowledge. Based on IF-sets, the paper presents the design of tree hierarchical IF-inference system of Mamdani type working more effective than a hierarchical FIS as it provides stronger possibility to accommodate imprecise information and, at the same time, the number of if-then rules is reduced compared to the IF-inference system.

Thus, the relationships among SDIs [52], [53], [54] and the weights of SDIs are incorporated and, at the same time, the system is comprehensible to its users due to a low number of if-then rules in the tree hierarchical IF-inference system of Mamdani type. The output of the hierarchical IF-inference system uses the theory of general IF-inference system. The introduction of association index ξ makes it possible to point out the classification of the i-th object $o_i \in O$ into the j-th class $\omega_j \in \Omega$ which was realized by the tree hierarchical IF-inference system initially. The model design was carried out in Matlab in MS Windows XP operation system.

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