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Combining System Dynamics and Agent-Based Simulation to Study the Effects of Public Interventions on Poverty

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Abstract

Poverty is a multidimensional social phenomenon that occurs in every economy around the world. Counteracting poverty is one of the tasks of public administration units. Under many programs financed from public funds, various tools and instruments can be used to combat poverty, but their implementation should be preceded by an in-depth analysis of the effects generated by their use. This is not easy, because the phenomenon of poverty is very complex, results from the arrangement of many interrelated heterogeneous elements, and the effects of actions are visible only after a long time. Hence, research in this area requires the use of an approach that can cope with the complexity of this phenomenon in dynamic terms. The aim of the article is to present the concept of a hybrid simulation model for studying the impact of public intervention on the level of poverty at local, regional and national level. The model is a hybrid of two computer simulation methods: System Dynamics (SD) and Agent-Based Simulation (ABS). SD method is used to model macroelements of the examined system (e.g. GDP level, labor market) and microelements (e.g. households and their members) are modeled using ABS. The article also shows the results of verification and validation of the proposed solution performed using the model for a case study. The presented solution can be used both by public administration units at various levels as well as by scientists - to conduct socio-economic research.

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Keywords: poverty; public intervention; hybrid simulation; System Dynamics; Agent-Based Simulation.

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1. Introduction

Poverty is a multidimensional social phenomenon that occurs in every economy around the world. Counteracting poverty is one of the tasks of public administration units represented by various actors, bodies and institutions, both at central and local level [1]. Activities aimed at poverty reduction focus primarily on the use of social policy tools related to various forms of government redistribution [2] and are usually public interventions, i.e. activities involving public resources [3]. However, public intervention does not always lead to the expected improvements. Therefore, prior to the implementation of a specific intervention, it is advisable to carry out an in-depth analysis of the expected effects of its implementation.

In practice, the effects of public intervention are most often assessed ex-post by means of evaluation performed by means of various methods. However, the essence of the evaluation process should not only be the observation of past events, but first of all the knowledge of planned activities results. In order to estimate them, various models are usually used [4]. However, a review of the models most frequently cited in the literature indicates that they were not designed to study the impact of public interventions on poverty levels [5]. Therefore, it can be stated that there is an evident need to develop a model that would be dedicated directly to the impact of public activities on poverty and would allow ex-ante evaluation not only at international or national level, but especially at regional and/or local level. It is also important for that model not to be one-off so that it can be used to anticipate the effects of various public interventions for poverty reduction.

This is not easy task, as poverty is a consequence of many factors, with mutual (mainly non-linear) interdependencies between them, which are often of a feedback nature and the effects of interventions are visible only after a long time ([2], [6]). In addition, the issue is complicated by the fact that some of these factors occur on a macro scale (e.g. GDP level, labour market), while others occur on a micro scale (e.g. GDP level, labor market), inne zaś w skali mikro (e.g. households and their members). Therefore, Authors believe that when assessing the effects of public interventions on poverty, a hybrid approach should be used understood as a combination of two or more computer simulation methods ([7], [8]). Hybrid simulation has become an increasingly common approach for modelling complex systems in the past two decades, as it provides a broader and better insight into the real system, since it allows the modelers to assess a given issue in different dimensions ([9], [10], [11]). It is important to note that many researchers claim that hybrid simulation provides a broader and better insight into the real system because it allows modelers to evaluate a given issue in different dimensions [12].

The aim of the article is to present the hybrid simulation model for studying the impact of public intervention on the level of poverty at local, regional and national level. The proposed model is a hybrid of two methods: System Dynamics (SD) and Agent-Based Simulation (ABS). SD method is used to model macroelements of the examined system (e.g. GDP level, labor market) and microelements are modeled using ABS. The article also presents the results of verification and validation of the proposed solution performed with the use of a model for a case study.

It is important to note that SD and ABS approaches are iconic in the way that they are often presented as exclusive alternatives to analyze complex systems ([9], [13]). Many scholars argue that the choice of an appropriate approach to adopt in a particular case should depend on the nature of the system at hand and the purpose of the model ([9], [13]). Swinerd and McNaught [9] suggest that many systems can be modelled in equivalent ways by both paradigms. However, they conclude that sometimes one paradigm presents a more natural choice than the other [14]. Some pioneering work on the linking System Dynamics and Agent-Based Simulation was conducted among others by Scholl [15], Schieritz [16] and Größler, Stotz and Schieritz [17]. Till date, many studies have been made on combining SD and ABS and the use of this hybrid to study problems in various disciplines, including studies on how to integrate the two approaches. The structured review of these studies can be found in [18]. None of the studies reviewed presented applications of the SD-ABS hybrid for research on poverty.

2. Main Features of the Proposed Solution

2.1. General model concept

The general structure of the model is presented schematically in Figure 1. The model consists of two sub-models: the Agent-Based and the System-Dynamics, between which there are relations of a feedback nature.

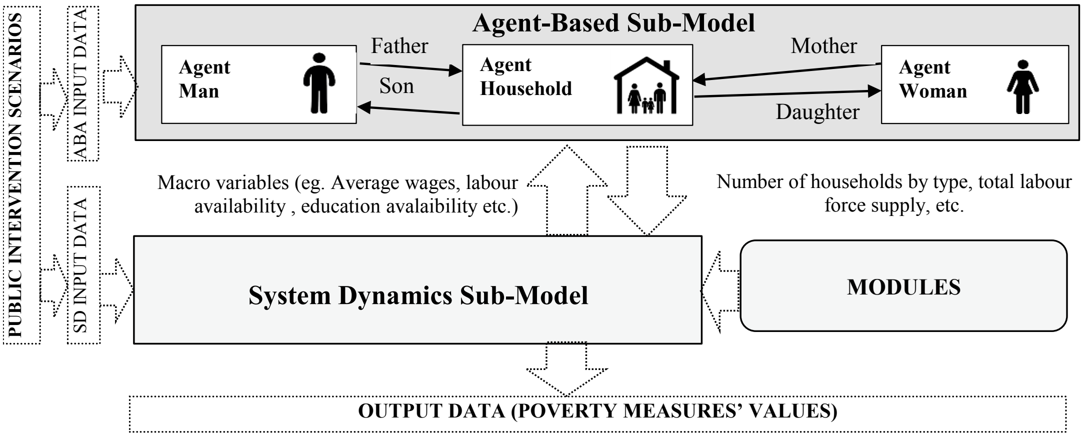

Fig. 1. General structure of SD-ABS hybrid model to study the impact of public intervention on the level of poverty (Authors' elaboration).

The Agent-Based Sub-Model (ABSM) consists of three types of agents: (1) male (M), (2) female (F), and (3) household (H), with the household agent being formed by combining a male agent (father) and a female agent (mother), while also being the source of M type (son) and F type (daughter) agents.

Each agent type is assigned certain features and decision rules. Both types of agents are described by such features as: age; probability of death depending on age; acceptable age difference from partner; education (primary, secondary, higher); age at first job (depending on education); age at retirement; socio-economic group membership (e.g. employee, farmer, pensioner, living on unearned sources); income group (determined on the basis of obtained remunerations, resulting from the multiplicity of the national average); current income level; source of income (e.g. from employment, self-employment outside agriculture, retirement or disability pension, from non-profit sources); degree of disability (zero value means no disability). The female agent has an additional feature defining the number of children (expected and current).

The agents' interactions and the way they function in the environment result from the decision-making rules assigned to them, for instance, the rule of pairing, getting employed, upgrading professional skills, and allocating income if they obtain employment. A female agent additionally has a decision rule assigned to her for having a child.

The third type of agent in the Agent-Based Sub-Model is the household agent. The most important features of this agent include: presence of a mother (0 - indicates her absence in the household); presence of the father; number of children, class of the place of residence (e.g., rural, urban). Moreover, each GD agent is assigned rules that are important from the point of view of poverty measurement, among them the rule of determining the biological type (e.g., one-person household, couple without children, couple with one/two/three/four and more children, mother/father with dependent children); calculating the number of household members, total household income and equivalent income; and determining the minimum income per person eligible for social assistance benefits. In addition, rules are defined for identifying the head of the family and marriage breakdown (probability of divorce may be a measure here), as well as the household's reliance on welfare benefits.

In order to determine the values of features of all agent types and to establish detailed rules of the agents' functioning in the environment, we need input data that, in some cases, result from legal regulations (e.g., the retirement age). Input data can also be calculated based on publicly available statistical data (e.g., probability of childbirth in relation to age or probability of childlessness) or developed according to the survey results. Data may also come from experts, who have expressed their opinions in reports, publications, etc., or through direct individual or group interviews or from expert panels. An important group of input data comes from the System Dynamics Sub-Model (SDSM), i.e., macro-variable values, on the basis of which agents undertake appropriate actions according to operating rules assigned to them.

The Agent-Based Sub-Model is designed to reflect in a disaggregated way the demography and population of a given area in which poverty is to be measured. It can refer to a specific geographical unit, for example: a gmina (municipality), a poviat (county), a voivodship (province) or the whole country - depending on the needs. The populations of "female", "male" and "household" agents initialized during the computation process correspond to the numerical quantities observed in a given area.

The data transferred from the Agent-Based Sub-Model to the System Dynamics Sub-Model are primarily the data on the number of households determined for the area under study, e.g., the households in general, as well as the households with specific features, including those with equivalent income below the poverty line. Having obtained the data calculated in the ABMS, it is possible to determine in the SDSM basic poverty indicators, both one-dimensional (e.g., headcount ratio, poverty gap index, income gap index) as well as multidimensional measures [19] by household type. The index values set in this module permit the assessment of the impact of planned public interventions on the level of poverty.

Besides calculating the values of individual poverty indicators, the System Dynamics Sub-Model is designed to map the macroeconomic factors that affect the poverty level and the relationships between them. Consistent with the nature of the System Dynamics method, these factors are modeled in the aggregate. Due to the multiplicity of factors, the SDSM is built on a modular approach. It assumes that modeling of systems consists in creating a "model of models", i.e., a heterogeneous structure composed of many structural blocks, called modules [20]. In the case of the presented Sub-Model, each module refers to a specific macroeconomic factor that, according to the literature, has an impact on poverty levels, for example: GDP, health care, education, labor market, etc. The set of modules can be freely extended not only by defining new modules basing on observations and on theory concerning the examined system, but also by adapting ready System Dynamics models relating to the modeled macroeconomic factors.

For different variants of intervention, separate SD sub-models have to be constructed and calculations are performed in conjunction with the Agent-Based Sub-Model, with data exchange between the modules taking place at each step of the simulated time. The results obtained by simulation for each individual option may be the basis for the choice of a specific intervention that will produce the desired effects in the form of poverty reduction.

2.2. Model implementation

It is possible to use a low-level programming language to create hybrid simulation model, but it is time-consuming and requires right skills as there would not be any specialized program in automating the work. Many hybrid models were constructed by only using a SD program (e.g. [21], [22]). This usually requires the use of arrays to be able to cope with added complexity [23]. Some models (such as [24]; [25]) used another tools in combination with a SD program. This can be done by either using some middleware or creating a separate code using a low-level programming language [23]. Currently, there is also existing commercial software, which is able to do both SD and ABS modeling, for instance Anylogic™. And final way to create the hybrid simulation models is to build an own platform for the work - and this particular method has been applied in this study.

For the purpose of the model implementation, a simulation computer program was developed in C# language in Microsoft Visual Studio environment. This approach was chosen in order to facilitate the communication process between the ABS and SD Sub-Models. The main blocks of the program and the relationships between them are shown in Figure 2.

The computer program consists of five main blocks:

- ABS Sub-Model - implementing Agent-Based simulation.
- SD Sub-Model - implementing System Dynamics simulation.
- input/output operation block - responsible for loading data into the program and saving the results of the program to disk.
- indicator Calculation Block - responsible for calculating poverty indicators such as the extent of poverty, at-risk-of-poverty gap, etc.
- GUI - the interface for communicating with the program user.

Since the proposed solution implies that all household data will be counted in the ABS Sub-Model, while the SD Sub-Model will be responsible for simulating the macroeconomic environment (e.g., labor market), it has been necessary to create a communication block with the SD Sub-Model and vice versa. The household data prepared in the ABS Sub-Model are passed to the SD Sub-Model for the labor market simulation. In turn, the SD Sub-Model transfers to the ABS Sub-Model the data on the variables it has calculated (e.g., data about the income of employed individuals or the number of jobs, etc.). Moreover, it should be emphasized that such communication takes place both ways on an ongoing basis. The data needed for the calculation of the respective poverty rates are communicated continuously between the SD and ABS Sub-Models. In addition to the elements mentioned above, both Sub-Models have the ability to operate on their own variables that can be defined dynamically while the program is running.

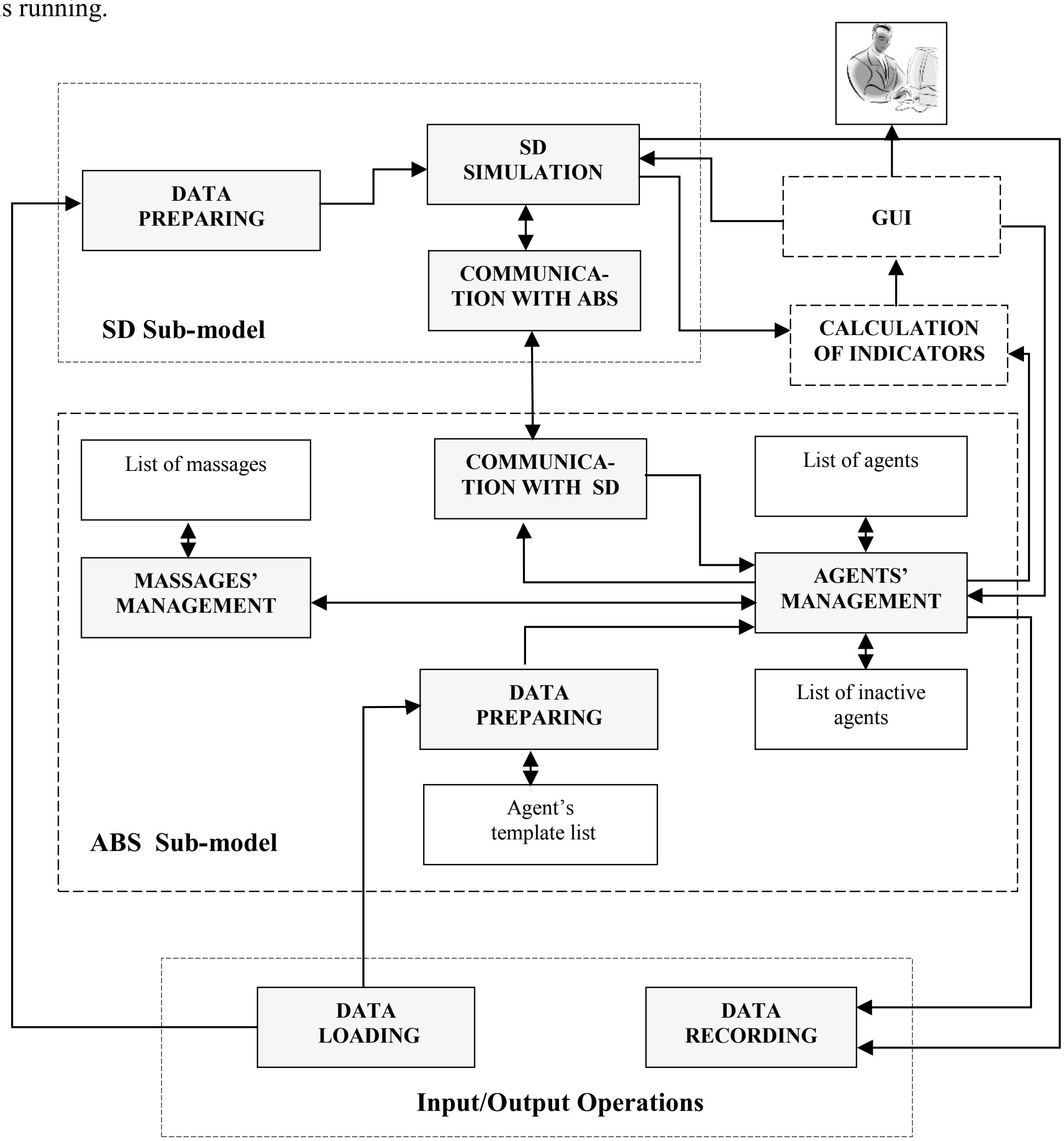

Fig. 2. The main blocks of a computer program and the flow of data between them (Authors' elaboration).

3. Model verification and validation

3.1. Simulation studies for a case study

One of the most complicated problems in the process of building a computer simulation model is to verify that the built model accurately reflects the reality [26]. To this end, the model was validated and verified using a case study.

As regards the analysis of poverty, the object of poverty measurement may be, for instance, the population of a given territorial entity on a given level (gmina, voivodship, region, country), and, alternatively, other populations, such as households of a given type, old-age-pensioners, the self-employed, employees, etc. In order to illustrate the universality of the proposed solution, we chose a territorial entity being a typical example of an average Polish gmina (small town) in the second decade of the 21st century. The case study is therefore a hypothetical small town in Poland with a population between 3000 and 6000 and a population structure similar to that of a country.

In order to conduct simulation studies for the case study, it was necessary to collect and estimate input data for both Sub-Models, as well as to make certain assumptions. The sources of data included e.g. reports from the Household Budget Survey [27], the European Union Statistics on Income and Living Conditions (EU-SILC) [28], and the Regional Data Bank of the polish Central Statistical Office [29].

The first simulation calculations made using the developed computer program served calibration and setting of initial values. Once satisfactory results were obtained, that were consistent with the logic of the system under study, the actual simulation phase proceeded. The simulation experiments were covered 8 periods (years).

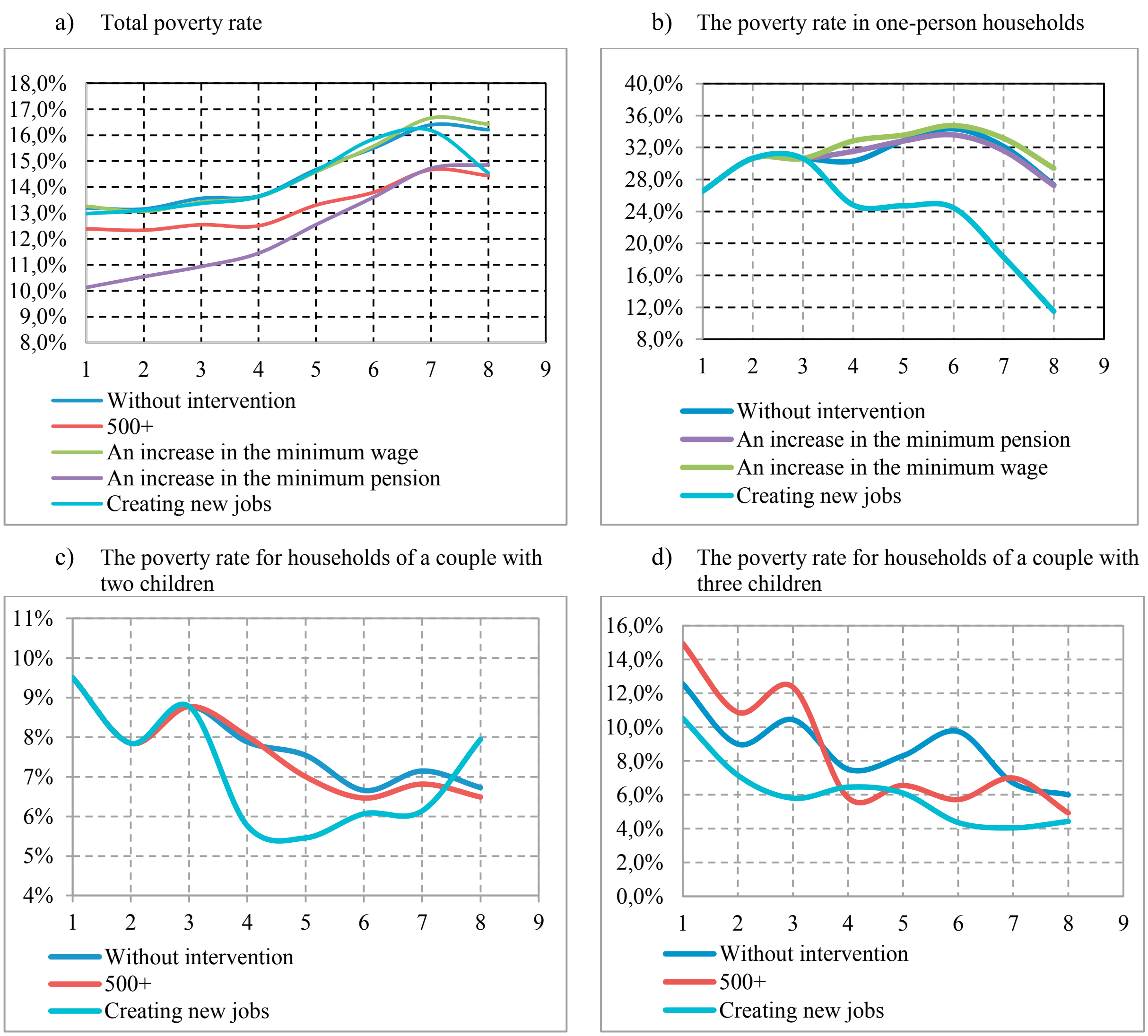

Fig. 3. The extent of poverty in subsequent iterations (years) (Authors' elaboration)

The following selected public interventions were analyzed in the simulation studies:

- state aid for families with children (the 500+ Program),
- an increase in the minimum wage,
- an increase in the minimum old-age pension,
- creation of new jobs.

There were selected public interventions whose usefulness for various state policies, e.g., pensions, labor market or family policy, could be tested. Demonstrating the universal applicability of the model will determine the degree of its utilitarianism.

Each of the above-mentioned interventions was tested in a separate experiment. Importantly, in order to eliminate the element of randomness in the simulation study, each experiment was repeated 10 times and the arithmetic mean was calculated on this basis. Example results of the simulation calculations are shown in Figure 3. The results obtained during the simulation experiments were the basis for the validation of the proposed solution.

3.2. Face validation

In order to check the validity of the model, face validation was applied by conducting individual interviews with domain experts [30]. This validation method was chosen based on the following premises:

- limited access to statistical data on households, population income, detailed household structure, etc.,
- high degree of the available data aggregation – the national level, which makes it impossible to relate the results to the data about gminas, cities or towns,
- lack of uniform methodology for counting poverty rates,
- the interdisciplinary and complex nature of poverty,
- lack of similar models to compare outputs.

The experts were surveyed through an interview questionnaire, which consisted of two main sets of questions about: (1) Consistency of model mechanisms and properties with the simulated reality and with the theory regarding the analyzed processes; (2) Empirical validation of input and output data.

The interview was conducted according to the following scenario: first, the expert was given a detailed overview of the assumptions and logic of the model and then the agents' behavior resulting from their qualities and decision rules was discussed. Next, the input data and how their values were estimated were presented. At the end of the interview, the results of the model and the methods used to calculate individual indicators were outlined.

In the next stage of the interview, the experts rated each item included in the interview questionnaire on a scale from 1 to 5, where 1 meant strongly disagree and 5 meant strongly agree with the statement in the question. In addition, the experts were asked to justify their rating.

Interviews were conducted with experts in economics, social policy, and computer science (computer modeling and simulation). The experts represented the world of academia and/or practice. A total of eleven interviews were conducted. Five experts represented the world of science, four were practitioners, and two experts combined science and practice. Their fields of expertise included: economics (3 experts), social policy (3), economics and information technology (2), economics and social policy (1), and social policy and information technology (1). The experts worked for the government and local administration sector, science sector and private sector (consulting industry).

A total of 97 valuations were made (two experts did not answer one question). The vast majority (76%) of answers were at the level of 5 (strong agreement), 18% were at the level of 4, and 6% were at the level of 3. The highest scores (mean 4.9) were given to the consistency of the poverty rate calculation in the presented simulation model with the theory of poverty measurement. The relatively lowest scores (mean 4.5) were given to the questions about the degree to which the agents' behavior represented the actions of individuals and households in the real world, and the degree to which the results and inputs were correct in the simulated case.

Experts representing the field of economics paid attention in particular to issues related to macroeconomic variables and elements of behavioral economics. On the other hand, representatives of the social policy area pointed to issues related more to social factors, e.g. internal and economic migration, non-profit sources of income (nonmaterial factors). Representatives of the computer science area, on the other hand, focused on the way the model functions (dynamics and agent programming), as well as on practical aspects, such as the costs associated with creating the model or a user-friendly interface. Representatives of all areas agreed on the usefulness of the assessed tool for the preparation of analyzes for decision-makers creating social policy at the central and local government level.

As could be expected, representatives of the science world paid more attention to the methodological aspects of creating a model (selection of variables for the model and relations between them), and practitioners - to the utility aspects and possibilities of using the model in social policy.

It is worth adding that the experts during the interview, apart from assessing the correctness of the model, also more broadly referred to the proposed concept. Among other things, they postulated further development of the model, e.g. by extending it with further interventions (e.g. housing or other government initiatives) and / or including more variables (e.g. macroeconomic). They also emphasized that the simulation results may initiate a discussion about the direction of changes in social policy and emphasized the importance of the scientific issue in the model.

To sum up the results of the conducted face validation, with the average of experts' answers to individual questions ranging from 4.45 to 4.9 (overall average 4.7), the correctness of the model was rated very highly.

4. Conclusion

The main objective of the proposed simulation model presented in the article is to provide information on the effects of public interventions being a part of anti-poverty activities implemented by public administration. The proposed concept of a hybrid model built with the use of two methods of computer simulation – System Dynamics and Agent-Based Simulation, makes it possible to avoid their individual constraints and allows for a more complete use of the potential of their complementary features, hence more accurate representations of complex dynamic systems can be provided.

The proposed solution permits the analysis of the problem in dynamic terms, at different levels of administrative division and in a comprehensive manner, thus allowing the analysts: (1) to capture the interrelationships (including feedbacks) between all the elements under study, i.e. households and their social-economic environment, (2) to determine the value of all the elements included in the analysis at each point in time for which calculations are performed, (3) to describe with adequate detail all the types of households under consideration, taking into account the decision rules governing the behavior of the household members.

Conclusions from the research allow us to outline the guidelines for further work on the proposed concept, including:

- developing further System-Dynamic modules relating to socio-economic variables,
- conducting in-depth studies that allow for a more refined representation of the decision rules assigned to agents (e.g., studies on the probability of divorce by age and social status),
- testing other public anti-poverty interventions using the model,
- incorporating in the model additional factors such as migration or withdrawal from labor market in favor of social transfers,
- developing a user-friendly interface to facilitate the introduction of new public interventions and the study of their impact by analysts.

Models created on the basis of this concept can be used by: (1) public administration units, and first of all government departments responsible for social security, (2) local government units - while creating voivodship programmes and general strategic documents (e.g. strategy of solving social problems at the commune level), (3) non-governmental organizations, (5) research organizations - in order to conduct simulations as a part of their social and economic research.

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