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The Rule-Based Model of Negentropy for Increasing the Energy Efficiency of the City's Digital Transformation Processes into a Smart City

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Citation: Orłowski, C.; Cofta, P.; Orlowski, A. The Rule-Based Model of Negentropy for Increasing the Energy Efficiency of the City's Digital Transformation Processes into a Smart City. *Energies* **2022**, *15*, 1436. https://doi.org/10.3390/en15041436

Academic Editors: Małgorzata Łatuszyńska and Gianfranco Rizzo

Received: 30 December 2021
Accepted: 10 February 2022
Published: 16 February 2022

Abstract: The aim of the article is to build a rule-based model (RMFDN) for increasing the energy efficiency of Smart Cities' digital transformation processes. The problem that arises during the implementation of digital transformation processes concerns the measures that should be assigned to estimate the duration of the digital transformation. Previous studies of digital transformation have been based on the analysis of design processes based on key performance indicators (KPIs), their place and role in the digital transformation processes, and their monitoring with the use of information architecture. The analysis of the digital transformation processes of cities into Smart Cities shows that they seem inappropriate to the complexity and uncertainty of the digital transformation carried out. The new approach presented in the article is based on three key aspects: rule-based description of the state of digital transformation processes enabling their energy assessment, introducing energy maturity capsules to describe the state of these processes and application of measures based on project negentropy increments for maturity capsules.

Keywords: process energy efficiency; Smart City projects; project negentropy; energy maturity capsule

1. Introduction

The aim of the article is to build a rule-based negentropy model (RMFDN) to increase the energy efficiency of the city's digital transformation processes into a Smart City. The processes of digital transformation are a complex utilitarian and research problem appearing in many publications [1]. This is a problem mainly of digital transformation of enterprises, but also considering the complex aspects of transformation of public organizations [2]. For this reason, various solutions are used, based both on the construction of digital transformation policies, as well as the use of a set of good practices to implement and support digital transformation processes [3]. In many publications [4], there are case studies of digital transformation policies, attempts to adapt these policies for new cities and now consider the role of clients and projects in building these policies [5].

The literature contains numerous definitions of a Smart City, which vary depending on the author's area of interest. The influence of technology on the development of the city is most often emphasized, but today, more and more often, smart city emphasizes other areas, e.g., the involvement of residents in the city's development. It should also be remembered that the technology in Smart City is only a tool, not a goal in itself. What is crucial is that Smart City should be seen as a stage in the development of a city, not an objective to be achieved [6].

Other publications [7,8] indicate the place and role of information architecture of enterprises and information architecture of cities for the analysis of potential increases in these processes. For this reason, four different processes for the development of digital transformation, as well as the monitoring of the status of these processes have been considered as applicable. The methods used so far to assess design processes and digital transformation as well as the state of the information architecture [9] were considered based on the key performance indicators. Other measures of aggregation of these processes, such as maturity capsules, were also taken into account.

This approach seems inadequate to the complexity of digital transformation processes. Therefore, the authors introduced new measures for the evaluation of digital transformation processes using their own preliminary work on the application of process maturity capsules [10] as well as urban metabolism [11]. They used the concept of negentropy to determine the state of energy capsules of the maturity of these processes using a rule-based model based on expert knowledge.

Therefore, the starting point for the construction of the proposed model is a completely different treatment of urban processes as those of urban metabolism [11] combining the subject of many disciplines, such as architecture, planning, city climate, city physics, sociology, and engineering. Hence, in the presented article, the city is treated as a thermodynamic system composed of open systems seen from the perspective of the maturity capsule of urban processes and their measures in the form of negentropy.

In the proposed RMFDN model, the authors of the study used maturity capsules to analyze the state of an IT project, as presented in the works [12]. If we assume that projects for Smart Cities are IT projects, we can then apply the maturity capsule to their evaluation, which means that we will also be able to apply similar solutions for process aggregation for digital transformation processes as well as information architecture.

The starting point for building the proposed model [13,14] is a completely different treatment of city processes as processes of urban metabolism [15] combining the subject of many disciplines [16,17] such as architecture, planning, city climate, city physics, sociology, and engineering [18]. Therefore, in the presented article [19], the city is treated as a thermodynamic system [20,21] composed of open systems seen from the perspective of the maturity capsule of city processes and their measures in the form of negentropy. It seems that the use of such an approach will allow the city to be analyzed as the dependence of two systems: thermodynamic and information systems for the analysis of digital transformation processes, which will be used to study the relationship between negentropy, and energy efficiency as presented in [22,23]. The design of the model also considers the concept of system equilibrium, assuming that in the state of equilibrium, the energy efficiency of the system is at its maximum [24,25]. Therefore, if we assume that in each open system there are two opposing complementary processes:

- Increasing negentropy: creating new system components that make up the system so that it runs smoothly,
- Increasing entropy—removing its components to reduce the efficiency of its operation.

It is the analysis of both negentropy and entropy processes that allows the system efficiency to be constantly assessed [26]. This approach was the basis for the construction of the RMFDN model, if the negentropy of the project, the negentropy of city maturity processes, the policy of building digital transformation and the negentropy of information architecture that can increase the energy efficiency of the digital transformation processes of the city into a Smart City.

This approach was the basis for building the negentropy flow model, if the negentropy of the project, the negentropy of the city maturity processes, the policies of building digital transformation and the negentropy of the information architecture can create conditions for analyzing the flow of this negentropy and assessing the state of implementation of projects for Smart Cities. This aggregation and extension of complex digital transformation design processes and information architecture in the case of using the maturity capsule and negentropy provides a common process analysis environment for the development of Smart Cities [26].

Therefore, the specificity of IT projects was presented at the beginning, indicating the place and role of the client, of the supplier and the state of the project for the assessment of the maturity capsule, considering the specificity of Smart City projects. Key performance indicators, as well as negentropy for estimating the energy efficiency of the processes, were indicated as a possible measure of these processes. Therefore, the importance of maturity capsules has been extended to energy maturity capsules so that they constitute the basis for determining negentropy for estimating the energy efficiency of processes. Subsequently, a similar specificity for the transformation processes of an IT organization is shown, considering the transformation processes of public organizations [27].

This narrowing of the problem and the lack of repeatability of the process in public organizations allows justifying the purposefulness of aggregating these processes with the use of the energy maturity capsule. It turned out to be purposeful to show the processes of designing information architecture, so important for the analysis of the state of the organization's processes, in our case, considering design and digital transformation processes. Then, with the presented conditions for the development of cities resulting from the implementation of digital transformation projects and the use of information architecture, a model proposal was presented that considers the assessment of these processes with the use of information architecture. The developed model was verified in terms of designing information architecture for the evaluation of digital transformation processes using energy maturity capsules and negentropy. Controlling the flow of negentropy allows for a completely different approach to estimating urban development processes for Smart Cities than the previously used key performance indicators.

2. Materials—Digital Transformation Processes

Building a rule-based model of negentropy to increase the energy efficiency of the digital transformation processes of the city into a Smart City is possible after prior introduction to the processes constituting the basis for building this model. Therefore, this part of the article presents the characteristics of the four main processes. The first one covers Smart Cities design processes considering their specificity. Then, the city development processes that are necessary for the implementation of Smart City projects are presented. The processes of developing the digital transformation policy based on the processes of urban development and Smart City projects are discussed successively. The summary presents the information architecture design processes that constitute the basis for the implementation of the model proposed in this article.

2.1. Processes of Smart City Projects

Smart City projects are a diverse group of projects implemented not only by the city for its residents, but also for other city partners. In many publications [10,12], there is a need to consider the requirements of residents at the stage of project implementation, because in many cases, the municipality implements projects to invite residents to participate. For this reason, Smart City projects can be divided into two groups: targeted at residents and directed by residents. The first group of projects includes infrastructure projects concerning both hardware, software, and many activities in this area. The second group includes educational projects whose main goal is to support the process of increasing digital awareness of citizens.

Both groups of projects have three basic components: a clearly defined goal, its customers, and its suppliers. Therefore, in many cases, such as in [13], attempts are made to classify projects considering the needs of a smart city. These needs regard the specifications of potential customers, such as residents, and specifications of suppliers, such as companies generating open data for the city's needs. For these reasons, Smart City projects are characterized by high uncertainty and diversified goals resulting from the needs of residents, and thus generate challenges for their implementation. Therefore, in these projects, friendly partners who coordinate activities among citizens, the city office and external partners (non-governmental organizations representing residents as the client of the project, and frequently acting as the client who puts demands on the project) are involved in the implementation processes. Ref. [28] defines project teams integrating business partners, non-governmental organizations and residents forming Smart Trio, Smart units being the stages of project implementation, as well as Smart Bus. Smart Bus is an example of an integration bus which involves the integration of Smart City project products on the one hand, and on the other, the search for new approaches to aggregating such complex aspects of IT projects implementation.

In [29,30], there is a need to use management methods based on soft approaches such as Agile, where projects are carried out in short project cycles to minimize the risk. There is also an attempt to classify projects from the point of view of the design process in [31]. In [32,33], there is also the concept of a maturity capsule aggregating complex design processes assessed from the point of view of design negentropy. Such a complex design environment indicates the need for a different treatment of the project itself or a group of projects. It also points to the need to include project goals in those of the city and try to assess the compliance of project goals with the goals of Smart Cities. For this reason, it seems advisable to evaluate existing Smart City projects in a completely different way and look for alternative methods of their evaluation considering the key aspects of these projects: technologies, customer maturity and the maturity of the supplier that implements these projects for Smart Cities.

2.2. Urban Development Processes

The previously discussed Smart City projects showed the importance of technologies, customer maturity and supplier organization maturity for the development of cities. This means that the success in the implementation of Smart City projects is largely a derivative of the development of city projects coordinated by the City Hall. Therefore, a question arises here: how should Digital Transformation projects integrating Smart City projects be developed? It seems that the development of these projects is to a large extent a derivative of the city's maturity.

The analysis of the state of literature [32] indicates a significant role in the development of Digital Transformation processes of urban development processes and their reference to similar cases in European cities as well as global trends in this area. Therefore, it seems advisable to point out the relevant methods and technology that are used by cities to assess their maturity. For this reason, three important components influencing this maturity are indicated below. The first of them, similarly to the Smart City projects, is the maturity of the inhabitants. In [33], it is indicated how important the assessment of this state is based on workshops carried out jointly with the residents to which representatives of the city's leading offices and the office responsible for the digitization process are invited.

It also indicates the need for in-depth interviews with key city figures. However, consultations with non-governmental organizations on the directions of the development of digital transformation expected by residents are of particular importance. It is stated that the tasks carried out in this way have a significant impact on improving the quality of life in the city and cooperation with its residents. They also influence the better management of the city by the employees of the city hall, as well as the rules for digitizing the city. It also indicates the principles and values that residents expect in the digitization process. They also suggest which principles and values should be assigned to specific activities and suggest factors that support and barriers to digital transformation, as well as ways to achieve them.

Another area that allows the city maturity to be assessed is the reference of the city's state to other European cities on the Smart Cities path. These cities have documents indicating the directions for the development of a smart city and promote activities in this area. If we look at the key cities in Europe that are on the path to Smart Cities, such as Berlin, Vienna, London, Helsinki or Amsterdam, it should be indicated that the documents and activities show the necessary activities for the city to achieve the status of Smart Cities. These activities include both preparatory activities, as well as those resulting from the publication of the digital transformation policy. They also include applications to be implemented because of the city's condition and policy contained in city documents. These documents also consider the principles, values, accents and priorities for such assumed tasks. Among other things, they point to the need to organize pilot ideas led by residents as well as the importance of infrastructure projects such as Amsterdam's Climate Street and West Orange. The need to implement Open Data projects for such areas of city development as mobility or infrastructure is also indicated.

The analyzed city maturity states can be related to global trends in the development of Smart Cities. The analysis of trends indicates two groups of them. The first one is directly related to the directions of development of digital transformations and the second-technological trends supporting the processes of digital transformation. Both groups of trends can be divided into present, emergent, and future related.

The analysis of digital transformation trends [20] indicated those aimed at changing the IT organization of city offices, as well as those related to the information architectures used in cities. It also indicates trends that take into account the use of change triggers and their impact on the development of cities. The same is done in the case of the analysis of technological trends, where those which use open data, IoT or Block Chain technologies as well as Big Data are considered. The importance of these technologies for supporting digital transformation processes is indicated. The maturity of the city seems difficult to assess due to the multiplicity of factors and the possibility of their quantification. Therefore, new solutions are sought for assessing the maturity of cities.

2.3. Processes of Development of the Digital Transformation Policy

After introducing the maturity of the city on the way to Smart Cities, the processes of developing digital transformation policies of cities have been presented in turn. The term digital transformation should be understood as the overall transformation of the city for the implementation of the Smart City concept. Both the process and technological conditions should be understood so that the digital transformation policy could be introduced to the city. It is necessary to refer to the conditions under which this policy will be introduced. It is also necessary, as presented in the previous chapter, to take into account both the maturity of the city and the conclusions resulting from the projects implemented by the city and influencing this maturity.

The city's digitization policy has three main components: data, technology and services. The process of building such a policy significantly fits in with the concept of building information architectures in cities. It is creating rules, principles and values for changes in the field of given technologies, services and processes. Their introduction allows for the creation of such conditions in the city that are necessary for the implementation of the digital transformation policy. In the case of building policies for various cities in Europe, it can be stated that the policies include identification of the directions of city development, the necessary values that are assigned to these directions and the principles that enable the implementation of these directions and assigning them appropriate values.

Therefore, in the case of building digital transformation policies [34], it is important to indicate the directions of digital transformation. In many cases, the determinants of cooperation with residents are considered, such as joint activities. The involvement of residents in the process of building digital transformation is also considered. The importance of a distributed data processing flow is indicated, or it is said directly about designing the city's information architecture. These directions become necessary for assigning specific values to them. Knowing the digital transformation policy for the city, one can also determine the implementation status of this policy based on the assigned values. Examples of such values are the launch of urban digital services to support the community of residents. An example of such values is also the implementation of Open Labs technology to increase the digital competences of residents. It is dependent on the directions and assigned values that we can determine whether the implemented projects corresponding to the city's maturity level translate into a change of the city to a Smart City.

The digital transformation policy is primarily the need to define the rules necessary to determine the method of achieving these values for the assigned directions and their values. Therefore, digital transformation policies for cities such as Barcelona and Helsinki include many very precisely defined rules of conduct that allow the city to develop. The principles adopted in the policy of transformation derive from directions and values. This means that the rules are defined for specific directions and values. Therefore, we can add further rules for the appropriate directions and appropriate values, which are a consequence of those applied. As a rule, the number of principles is significant and suggests whether the extent of the digital transformation policy being built is feasible. For example, for the value of high digital competences for the city, the principle of testing the level of digital competences of residents is introduced to minimize or eliminate inequalities in access to digital services.

In this case, the principle of designing and implementing digital services also applies so as not to restrict anyone's access to these services. The number of principles, as mentioned, is significant, while it is important in the digital transformation policy, when identifying values and principles, to show their relation to the information architecture built in the city. The construction of information architecture will be discussed in the next chapter, while both the pre-discussed projects and the maturity of the city or the directions, values and principles of the transformation policy are important here. It is also of significance that they fit into the city's information architecture as an environment for verifying the usefulness of information architecture for the development of digital transformation.

In addition to the description of the processes of building a digital transformation policy, it is also worth mentioning that the inhabitants, as well as IT organization and the municipality, are responsible for its implementation. Non-governmental organizations and the scientific and research community, which coordinates the cooperation between the sectors responsible for the implementation of the transformation policy, are also of importance. Moreover, the description points to the place and importance of the private sector, primarily in the implementation of digital transformation projects, as responsible for the implementation and coordinator of these processes. The combination of politics, its directions of values and principles, together with the entities responsible for implementation, allows us to look at the construction of the digital transformation policy as a set of processes with disorganization. It also allows us to see them as interpenetrating processes that are required, apart from the detailed descriptions typical for policies, and to treat them as a kind of model that can be used for the implementation of these processes.

2.4. Information Architecture Design Processes

Building the city's informational architecture is a complex process mainly involving representatives of city offices. The available literature [12,28] shows the version of the construction of information (information) architecture of the city and its condition, method of implementation and expectations. These expectations can be seen from the perspective of digital transformation trends in order to ultimately show the existing documents containing both the vision of architecture and the way of implementing this architecture for the city's needs.

It is assumed that the city's information architecture based on the standards of information architecture adopts three forms of implementation in cities. The first is the classic information architecture compliant with the TOGAF standard. The second is digital information architecture, which is a version of the classic information architecture, taking into account the process of adapting this architecture to the city's needs. The third form is a specially designed information architecture based on information architecture for Smart Cities.

For examples and how to implement these architectures, one may refer to the list of publications. It should also be assumed that the current form of the city's information architecture is based on information architecture. Digital information architecture is a trend of the future, adaptation of compositional architecture to the needs of Smart City. In case a city decides to build the city's information architecture, it should be assumed that the description of the design processes of this architecture also includes the guidelines that should be followed to maintain the consistency of individual IT solutions created as part of the information architecture.

Most of these solutions are based on the design standards developed by The Open Group. In many cases, it is assumed that the process of building the city's information architecture is incremental in nature, in which individual entities such as city users and residents, tourists and business influencing the city's development are involved. It is assumed that they have a significant way of developing this architecture. It is also assumed that the created information architecture of the city must be compliant with the documents created in the city, such as documents on the city's development towards Smart City, legal documents confirming the importance of information architecture, as well as long term city development strategies until 2030 or beyond.

In the construction of this architecture, the key processes that should be considered are also indicated in order for the information architecture to meet the requirements of residents. Examples of such processes are the problem of the autonomy of districts, traffic jams in the city of closed and open data, queues in offices or the problem with finding parking spaces. For this reason, in the first step, goals are created for the information architecture vision. As a rule, the list of goals is large; hence, the priority procedure is adopted. An example of such goals is shortening the time of providing services, intelligent and comfortable getting around the city or reducing the number of people using cars.

The next step in building the city's information architecture is determining the results of the implementation of the adopted goals. Hence, the form of the city platform for the integration of services and data or the analytical and monitoring tools for the implementation status of the city's information architecture are determined. To create a vision of the functioning of information architecture, it is necessary to analyze the environment and its potential. For this reason, government documents, plans for the provision of services and authentication systems for system services in state archives, and e-payments are integrated.

The lack of such an approach does not allow for the proper location of the city's information architecture, considering its surroundings. For this reason, as part of the work on the vision of architecture, the necessary competences are defined for the implementation of the adopted goals, which are, for example, building competences, development and maintenance of IT services or publication and sharing of data. The next step is to build a model of the city's information architecture. This model of city information architecture should consider three layers: business, data and application.

Hence, in the business layer, it is necessary to define the structure and model of services that will be implemented for the city's needs, and then to adopt goals for these services. The next step is to build a data layer model where open data that are necessary for monitoring are determined. These are, for example, data on office statistics, data from IoT devices and personal data to name a few. After creating a data layer, the next one is created as the application layer. The creation of this layer is a consequence of mapping services, which in turn result from the business layer created earlier.

The lack of links between the application layer and the service layer results in a lack of consistency in the structure of the information architecture. Examples of such applications are those related to access to services and data, communication platform, IoT devices, open APIs or building a database and applications. The production environment, integration rails and, above all, infrastructure are included here. Therefore, the technologies include both available communication protocols, websites of city creators, as well as communication networks allowing access to data.

For the implementation of individual layers, it is necessary to adopt architectural principles when designing information architecture. Architectural principles include best practices related to the design and implementation of data, technologies, and applications; these are also the best practices related to the use of maps and business processes to define city processes. Design principles apply to individual design layers. Hence, when designing information architecture and designing its individual layers, one should consider a group of design cycles adapted to the design of individual layers.

3. Materials—Energy Capsules of Digital Transformation Processes Maturity

In this part of the article, basic concepts will be introduced to formalize the relationship between the size, quality and significance of Smart City projects, city maturity, digital transformation policy and information architecture. It seems that, on the one hand, the presented descriptions fully exhaust the problems of urban development to Smart City, but to support the transition to this path, it is necessary to present and propose certain formalisms, so important both for the definition of negentropy and energy capsules of maturity.

The article adopts the cybernetic concept of negentropy (ordering), which is inconsistent with its physical prototype (a measure of disorder or dispersion) and is also a vector quantity. The use of the negentropy concept will facilitate the management of digital transformation processes in the ongoing assessment of the state of the project by determining the energy efficiency of the processes, which will enable taking appropriate management decisions in a quick manner, and thus increasing the chances of completing the project.

The article also adopts the standard energy efficiency of processes, which is the ratio of the amount of energy saved compared to the amount of energy consumed (or forecast consumption). The definition adopted in this way allows for such energy management as to minimize its consumption in the processes of production, exploitation or running a business.

Having experience in the field of formalization of social processes, the authors of the article, also proposed using negentropy to analyze the processes of digital transformation. Negentropy appears to be based on Zadeh's statement, "If the complexity of a system increases, our ability to make accurate and meaningful statements about its behavior decreases until it reaches a threshold value beyond which precision and relevance become almost mutually exclusive characteristics" between the complexity of the processes and the possibility of their formal evaluation. Therefore, we propose a design negentropy RMFDN model to monitor the status of these processes. To present this model, it is necessary to define the concept of the energy maturity capsule and its measures.

When defining the maturity capsule, the terms used to describe the maturity capsule for IT projects published in [17,20] were used. The concept of the maturity capsule was defined as a set of assessments of the state of the processes: the maturity of the Smart Cities design processes, the city development processes, the processes of preparing the city's digital transformation policy and the process of designing the city's information architecture. It was assumed that the measure of the processes for this capsule is the degree of order, which is negentropy. A detailed matrix-vector description of energy maturity capsules as well as a scalar and vector description of negentropy is presented below. For these assumptions, it was found that, for example, the processes of digital transformation at the moment of its initiation are characterized by, according to the adopted convention, a low negentropy, which increases during its implementation (as opposed to physical entropy).

The terms used to define the maturity capsule for IT projects published in the works [31,34] were used. It was assumed that the maturity capsule for IT projects as well as its negentropy would constitute the basis for determining the energy maturity capsules for the city's maturity, the processes of preparing the city's digital transformation policy and the process of designing the city's information architecture. The concept of the maturity capsule was defined as a set of assessments of the maturity of the supplier, customer and project organization (estimated by the scalar negentropy of the project), constituting the basis for assessing the state of an IT project. Then, it was assumed that the measure of processes for this capsule reflecting the degree of order, which is negentropy. For these assumptions, according to the adopted convention, it was found that the processes of digital transformation, at its initiation, were characterized by low negentropy, which increased during its implementation (unlike in the case of physical entropy).

The concept of the energy maturity capsule also fits into the processes of modeling complex systems, where the processes that are subject to initial processing are initially prepared and then, thanks to the maturity capsule, they are aggregated for the needs of the decision model variables. Such a model becomes the basis for the creation of decision systems with the use of rule-fuzzy implementations in which linguistic values are described by means of negentropy, and this approach was used in the implementation of the maturity capsules proposed in the article.

When describing the energy capsules to maturity, elementary mathematical tools, matrices, and vectors will be used, and a linguistic approach will be applied that creates conditions to increase the usefulness of the models created. Then, the developed model using linguistic description will constitute a universal useful value used by cities.

To determine the assessment of the state of digital transformation processes, we propose to introduce the concept of multidimensional negentropy of the project together with appropriate measures (measures). The concept of vector secondary (secondary) negentropy, which is fundamental in the concept of the work, is based on the two components adopted for given capsules. To correctly interpret these variables, we suggest mapping the primary (primary) negentropy described in the 3D space into the above-mentioned vector (secondary) negentropy given in the 2D space—using appropriate PPW processing. This approach (and the transition from 3D to 2D) facilitates the measurement (determination) of the negentropy value both in the 2D vector version (secondary) and in a convenient scalar negentropy (tertiary) version.

3.1. Energy Capsule of Maturity of Smart Cities Design Processes

In this way, we come to the possibility of formulating a complete description of the digital transformation processes contained in the integrated K-D-P maturity capsule, which allows for an effective and complete quantification of the maturity state of projects, cities, policy and information architecture, respectively. Wherever we talk about negentropy—without specifying this concept, we mean design negentropy treated as a tool concept for assessing the state of the maturity capsule. The multidimensional definition of negentropy allows for spatial (richer than scalar) representation of the analyzed concept (negentropy and the trajectory of its variability), which—from the point of view of the evaluation of digital transformation processes—substantially extends the possibility of analysis. Using only a scalar description would limit the possibility of studying negentropy—as a closed, scalar representation. Therefore, to define the maturity capsule of Smart City projects, the primary (primary) negentropy described in the 3D space was initially defined.

$$\boldsymbol{n1_t} = [p_t \; c_t \; s_t \,] \tag{1}$$

where:

$\boldsymbol{n1}_t$—three-dimensional design process maturity capsule;
$n1_t$—negentropy of the design processes maturity capsule, $n1_t \in <1, 5>$;

p_t—vector of maturity of applied information technology;
c_t—customer maturity vector;
s_t—vector supplier maturity.

Then, for the energy maturity capsule, you can define vector negentropies of its components: the maturity of the technologies used, the customer and the supplier. For the maturity of the IT technologies used, an example of vector negentropy determined based on the amount of IT technologies used and the knowledge of the project area by the supplier and the client was presented:

$$\boldsymbol{p_t} = [pn_t\ pd_t\ ] \tag{2}$$

$\boldsymbol{p_t}$—vector maturity of applied technologies;
pn_t—variable (used to) assess the amount of applied technologies for managing an IT project, $pn_t \in <1, 5>$;
pd_t—variable of the level of expertise, knowledge of the project domain—$pd_t \in <1, 5>$.

In many situations, experience has shown that the scalar assessment of $pn_t \in <0, 5>$ can also be extremely useful. In a practical approach, the synthesis of negentropy can be made based on a convenient linguistic assessment of its components. The maturity capsule defined in this way and negentropy constitute the basis for defining the remaining maturity capsules of the process flow model in the digital transformation of the city.

3.2. The Energy Maturity Capsule of the City's Development Processes

Similarly, as in the case of the project maturity capsule, the city development maturity capsule and the primary (primary) negentropy described in 3D space were defined at the beginning.

$$\boldsymbol{n2_t} = [t_t\ o_t\ w_t\ ] \tag{3}$$

where:

$\boldsymbol{n2_t}$—three-dimensional negentropy of the city development maturity capsule;
$n2_t$—negentropy of the city development maturity capsule;
t_t—vector of the maturity of technology development processes in relation to technological trends;
o_t—vector of the maturity of the processes of building a digital culture of inhabitants in relation to the trends of digital transformation;
w_t—vector of maturity of the processes of implementation of Smart Cities patterns in relation to Smart Cities in the world.

Then, for the city development maturity capsule, vector negentropies of its components can be defined: the maturity of technology development, the digital culture of citizens and the implementation of Smart Cities patterns. For the maturity vector of technology development processes, an example of vector negentropy determined on the basis of the development of the Internet of Things and Big Data technologies is presented:

$$\boldsymbol{t_t} = [pIoT_t\ pBD_t\ ] \tag{4}$$

$\boldsymbol{t_t}$—vector maturity design;
$pIoT_t$—variable (used to) assess the maturity of the processes of implementing the Internet of Things systems, $pIoT_t \in <1, 5>$;
$pBDt$—variable of the maturity level of Big Data system implementation processes—$pBD_t \in <1, 5>$.

3.3. The Energy Maturity Capsule of the Processes of Shaping the Digital Transformation Policy

The capsule of maturity of the processes of building a digital transformation policy is similarly defined as capsules of projects and cities. At the outset, its primary (primary) negentropy described in 3D space was determined:

$$\boldsymbol{n3_t} = [k_t\ z_t\ v_t\ ] \tag{5}$$

where:

$\boldsymbol{n3_t}$—three-dimensional maturity capsule of the processes of building a digital transformation policy;
$n3_t$—negentropy of the maturity capsule of the processes of building a digital transformation policy;
k_t—vector of maturity of the processes of designing directions of building a digital transformation policy;
z_t—vector of maturity of the design processes of the principles of building a digital transformation policy;
v_t—vector of maturity of design processes of value of building digital transformation policy.

Then, for the maturity capsule, we can define vector negentropies of its components: the maturity of the design processes: directions, principles and values of the digital transformation policy. For the maturity vector of the processes of designing the directions of building a digital transformation policy, an example of vector negentropy determined on the basis of directions for Smart Cities and existing policies for the analyzed city is presented.

$$\boldsymbol{k_t} = [pSC_t\ paC_t\ ] \tag{6}$$

$\boldsymbol{k_t}$—maturity of the processes of designing directions for building a digital transformation policy;
pSC_t—variable (used for) assessment of directions for Smart Cities, $pSC_t \in <1, 5>$;
paC_t—a variable for the assessment of the policies of the analyzed city—$paC_t \in <1, 5>$.

3.4. The Energy Maturity Capsule of Information Architecture Design Processes

The maturity capsule of the city's information architecture design processes is a key element in the process of negentropy flow. Its primordial (primary) negentropy is described in 3D space:

$$\boldsymbol{n4_t} = [pr_t\ te_t\ da_t\ ] \tag{7}$$

where:

$\boldsymbol{n4_t}$—three-dimensional maturity capsule of the city's information architecture design processes;
$n4_t$—negentropy of the maturity capsule of the processes of designing the information architecture of the city;
pr_t—vector of process maturity of process architecture design;
te_t—vector of maturity of technological architecture design processes;
da_t—vector data architecture design process maturity.

Then, for the maturity capsule, vector negentropies of its components can be defined: the processes of designing process, technological and data architectures. For the vector of maturity of the process architecture design processes, an example of vector negentropy determined on the basis of the process maturity of an IT organization and a city hall is presented.

$$\boldsymbol{pr_t} = [pIT_t\ pCC_t\ ] \tag{8}$$

$\boldsymbol{pr_t}$—vector of process maturity of process architecture design;

pIT_t—a variable (used to) assess the process maturity of an IT organization, $pIT_t \in <1, 5>$;
pCC_t—variable of the level of process maturity of the city hall—$pCC_t \in <1, 5>$.

4. Methods—The Rule Model of Negentropy for Increasing the Energy Efficiency of the Digital Transformation Processes of the City into a Smart City

In this part of the work, a layered rule-based model RMFDN will be presented. As mentioned before, various conditions influencing the process of building the rule model were considered. Negentropy was considered as a measure of assessing the condition of individual capsules, but also the possibility of using the increments of negentropy to assess the city's digital transformation processes was considered. It seems that negentropy increments will be easier to implement assuming the complexity of the maturity capsule and the possibility of using negentropy to assess the state of these capsules.

The use of the incremental approach in which the negentropy of digital transformation processes will be assessed based on the increments of negentropy of individual components will allow us to obtain an effect in which small changes will be easy to estimate. It will also allow for precise definition of the state of digital transformation processes. For this reason, the form of the function expressed by formula 9 has been discussed for a relatively long time. Is it supposed to be an incremental function where increases of negentropy translate into an increase in digital transformation processes, or negentropy of digital transformation processes will translate into a negentropy of increases in digital transformation processes?

Based on consultations with experts and the possibility of actual assessments of the state of project negentropy, an incremental approach was adopted in which both the negentropy of the maturity capsules as well as the negentropy of the digital transformation processes will be seen as increments of negentropy and not the actual states of design negentropy. This approach also corresponds to project management processes using soft approaches, in which it is easier to estimate the growth within individual sprints than to determine the actual values resulting from generalization in multiple sprints.

Therefore, the flow concept will be presented in the first Figure 1. It presents three layers-tracks of processes constituting the basis for a formal description: digital transformation processes, maturity capsules of these processes and negentropy increments for individual capsules as measures of their evaluation.

Then, appropriate formalisms for maturity capsules will be introduced, along with its vector and scalar measures, as well as assigning negentropy to these measures. The analysis of the flow of this negentropy will make it possible to capture weak processes and to indicate strong processes, which are so important from the point of view of the development of Smart Cities.

Let us first introduce the linguistic description. The rule-based variables are generated by the negentropy increment function Q_ψ. It expresses the rule-based implementation of the increase in digital transformation processes:

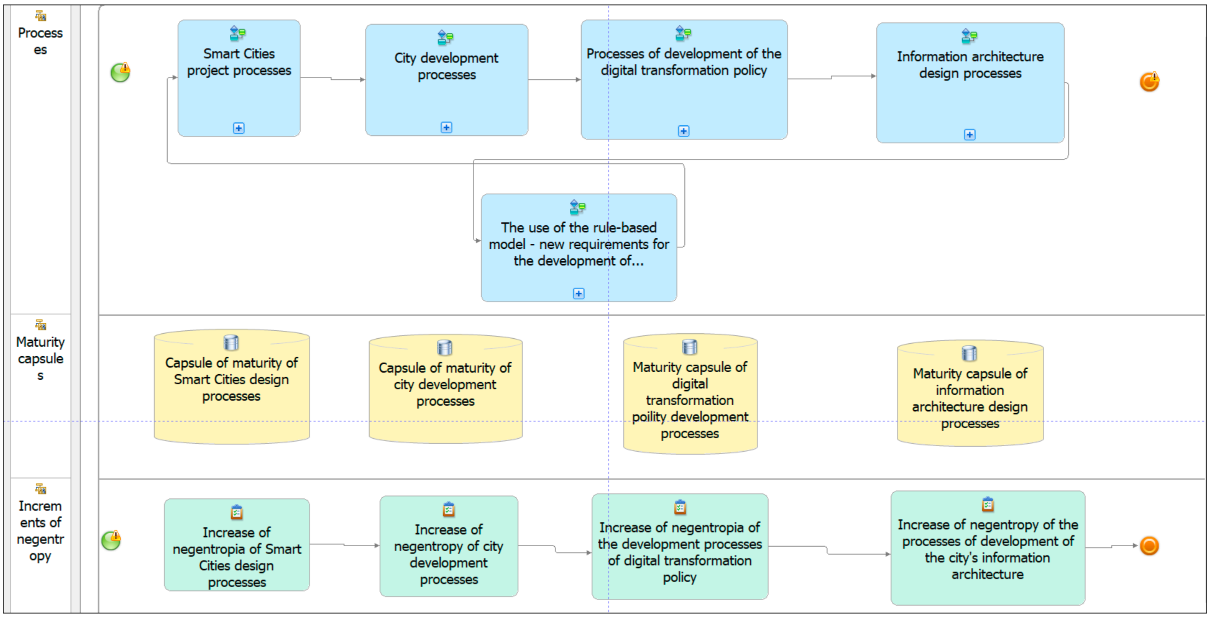

Figure 1. Layers of the negentropy flow model of the digital transformation processes project.

$$Q_\psi : \mathbf{\Delta} n_t \rightarrow \mathbf{\Delta} ndg_t \tag{9}$$

$\mathbf{\Delta} n_t$ —vector of negentropy increment of maturity capsules;

$\mathbf{\Delta} ndg_t$ —vector of negentropy of digital transformation;

Δndg_t —scalar assessment of the increase in negentropy of digital transformation, $\Delta ndg_t \in <1,5>$;

z_t —scalar evaluation of negentropy of the maturity capsule, $z_t \in <1,5>$.

$$\mathbf{\Delta} ndg_t = \begin{bmatrix} \Delta ndg1_t \\ \Delta ndg2_t \\ \Delta ndg3_t \end{bmatrix} \tag{10}$$

Since in the described rule-based subsystem, like the one presented in [34], there are no dynamic operations, using an economical description, the time index *t* may be omitted. Then, the basic variables of the described rule subsystem (Figure 1), the vectors of negentropy increment of maturity capsules, are presented as follows:

$$\mathbf{\Delta n}_t = \begin{bmatrix} \Delta n_t^k \\ \Delta n_t^o \\ \Delta n_t^p \end{bmatrix} = \begin{bmatrix} \Delta n^k \\ \Delta n^o \\ \Delta n^p \end{bmatrix} = \mathbf{\Delta n} \tag{11}$$

$$\mathbf{\Delta ndg}_t = \begin{bmatrix} \Delta ndg1_t \\ \Delta ndg2_t \\ \Delta ndg3_t \end{bmatrix} = \begin{bmatrix} \Delta ndg1 \\ \Delta ndg2 \\ \Delta ndg3 \end{bmatrix} = \mathbf{\Delta ndg} \tag{12}$$

When determining the level of use of IT methods and tools, it was assumed that linguistic quantities are represented by values from the sets {1, 2, 3, 4, 5} or {BM, M, S, D, BD}, where BM (very small or very low), M (low), S (medium), D (big or high), BD (very big or very high).

For the sake of simplicity, it was assumed that the linguistic values of the variables, the negentropy of the maturity capsule (Δn) and the output data (Δndg) are described with the same symbols as acute values. The linguistic model is based on the concept of processing with the function of increasing functionality, Q_ψ, which takes the form of a rule:

$$Q_\psi : R_{\Delta n} \to R_{\Delta ndg} \tag{13}$$

$R_{\Delta n}$ is a Cartesian product (set of fives) of sets of linguistic values for assessing the state of maturity capsules: $R_{\Delta n} = \delta \times \delta \times \delta \times \delta \times \delta = \delta^5$, $\delta = \{1, 2, 3, 4, 5\}$,

$R_{\Delta ndg}$ describes the Cartesian product of linguistic sets of values of changes in the level of digital transformation processes, $R_{\Delta ndg} = \rho \times \rho \times \rho \times \rho \times \rho = \rho^5$, $\rho = \{1, 2, 3, 4, 5\}$.

Based on the linguistic description with the use of the maturity capsule state assessment function Q_ψ, we can present this description in the form of a rule:

$$Q_\psi : (\Delta n^1 \textbf{ IS } \mathrm{A}_{1j}) \textbf{ AND } (\Delta n^2 \textbf{ IS } \mathrm{A}_{2j}) \textbf{ AND } (\Delta n^3 \textbf{ IS } \mathrm{A}_{3j}) \textbf{ AND } (\Delta n^4 \textbf{ IS } \mathrm{A}_{4j}) \Rightarrow (\Delta ndg^m \textbf{ IS } \mathrm{C}_{mn}) \tag{14}$$

where symbols $\mathrm{A}_{ij}, \mathrm{C}_{mn}$ describe linguistic values that are matrix elements

$$\mathrm{A} = [\mathrm{A}_{ij}] \qquad \mathrm{C} = [\mathrm{C}_{mn}] \tag{15}$$

and for i = 1, 2, 3, 4; j = 1, 2, 3, 4, 5; m = 1, 2; n = 1, 2, 3,

$\mathrm{A}_{ij} = a_{j-1} = j - 1;$ i = 1, 2, 3

$$\mathrm{A} = \begin{bmatrix} \mathrm{A}_{11} & \mathrm{A}_{12} & \mathrm{A}_{13} & \mathrm{A}_{14} & \mathrm{A}_{15} \\ \mathrm{A}_{21} & \mathrm{A}_{22} & \mathrm{A}_{23} & \mathrm{A}_{24} & \mathrm{A}_{25} \\ \mathrm{A}_{31} & \mathrm{A}_{32} & \mathrm{A}_{33} & \mathrm{A}_{34} & \mathrm{A}_{35} \\ \mathrm{A}_{41} & \mathrm{A}_{42} & \mathrm{A}_{43} & \mathrm{A}_{44} & \mathrm{A}_{45} \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 & a_5 \\ a_1 & a_2 & a_3 & a_4 & a_5 \\ a_1 & a_2 & a_3 & a_4 & a_5 \\ a_1 & a_2 & a_3 & a_4 & a_5 \end{bmatrix} = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \end{bmatrix}$$

Moreover, for i = 1, 2, 3, 4; j = 1, 2, 3, 4, 5; m = 1, 2; n = 1, 2, 3,

$\mathrm{C}_{mn} = c_{n-1} = n - 1;$ m = 1, 2, 3

$$\mathrm{C} = \begin{bmatrix} \mathrm{C}_{11} & \mathrm{C}_{12} & \mathrm{C}_{13} & \mathrm{C}_{14} & \mathrm{C}_{15} \\ \mathrm{C}_{21} & \mathrm{C}_{22} & \mathrm{C}_{23} & \mathrm{C}_{24} & \mathrm{C}_{25} \\ \mathrm{C}_{31} & \mathrm{C}_{32} & \mathrm{C}_{33} & \mathrm{C}_{34} & \mathrm{C}_{35} \\ \mathrm{C}_{41} & \mathrm{C}_{42} & \mathrm{C}_{43} & \mathrm{C}_{44} & \mathrm{C}_{45} \end{bmatrix} = \begin{bmatrix} c_1 & c_2 & c_3 & c_4 & c_5 \\ c_1 & c_2 & c_3 & c_4 & c_5 \\ c_1 & c_2 & c_3 & c_4 & c_5 \\ c_1 & c_2 & c_3 & c_4 & c_5 \end{bmatrix} = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \end{bmatrix}$$

The above description at the level of linguistic rules closes the presentation of the negentropy flow model, which may be the basis for further development and implementation, for example with the use of fuzzy description and the construction of knowledge bases (e.g., for the project negentropy variable). It is also the basis for including the whole problem in the framework of the decision support system in the implementation of digital transformation processes for Smart Cities. The previously presented model of negentropy pre-processing within maturity capsules is completely sufficient for the specification of variables for determining the increment of negentropy in maturity capsules for the needs of the negentropy flow model and its implementation in the form of a decision-making system.

5. Results

The developed model was subject to verification processes. Based on (14), 1024 (4^5) rules were created showing how the city develops on the way to Smart City. This process was carried out on two levels:

- Selection of negentropy increments in the flow model for 1014 rules with the help of Smart Cities experts;
- Application of the developed model to support the design of the city's information architecture.

The process of verifying the RMFDN model took place while building the digital transformation policy of Warsaw (Poland). It was included in the process of designing information architecture in which the model supported the design of the architecture vision. The maturity of the architectural vision layer was not included in the capsule due to difficulties in its assessment. Therefore, the use of the model was proposed to support the implementation of the information architecture vision layer. It is the vision of digital transformation that is a process that can be supported with the use of the model based on negentropy increments proposed in the work. Therefore, the study assumes that the increases in negentropy will be assessed in the sprints determined by the implementation of the information architecture design project.

The process of verifying 1024 rules was carried out in two stages. In the first stage, experts made them aware of the place and importance of negentropy. The question often arose why negentropy rather than entropy is the basis for process evaluation and why this concept of negentropy is used to evaluate maturity capsules. Now, when it was shown how important it is to look at the multifaceted and spatial process in which we define the state or status of a given process and use such linguistic measures, it turned out that identifying negentropy or negentropy increase for digital transformation processes becomes much easier.

Such a significant number of rules showed that, firstly, the rule evaluation process should be gradual, i.e., groups of rules should be analyzed, and secondly, it should be incremental. Therefore, after defining a few rules, examples of these rules are given below, why the process was discontinued, if you should consider setting up a website with access for experts who will be able to estimate the extent to which it is possible to verify the rules given there. A similar approach was used in the work in which the levels of the city's readiness to be a Smart City were analyzed. The following are examples of the inference process for model rules:

$$\begin{array}{l}
\textbf{IF } \Delta n_1 = \text{M } \textbf{AND } \Delta n_2 = \text{S } \textbf{AND } \Delta n_3 = \text{S } \textbf{AND } \Delta n_1 = \text{S } \textbf{THEN } \Delta ndg = \text{S} \\
\textbf{IF } \Delta n_1 = \text{M } \textbf{AND } \Delta n_2 = \text{M } \textbf{AND } \Delta n_3 = \text{S } \textbf{AND } \Delta n_1 = \text{S } \textbf{THEN } \Delta ndg = \text{S} \\
\textbf{IF } \Delta n_1 = \text{M } \textbf{AND } \Delta n_2 = \text{M } \textbf{AND } \Delta n_3 = \text{M } \textbf{AND } \Delta n_1 = \text{S } \textbf{THEN } \Delta ndg = \text{M} \\
\textbf{IF } \Delta n_1 = \text{S } \textbf{AND } \Delta n_2 = \text{S } \textbf{AND } \Delta n_3 = \text{S } \textbf{AND } \Delta n_1 = \text{M } \textbf{THEN } \Delta ndg = \text{S} \\
\textbf{IF } \Delta n_1 = \text{S } \textbf{AND } \Delta n_2 = \text{S } \textbf{AND } \Delta n_3 = \text{M } \textbf{AND } \Delta n_1 = \text{M } \textbf{THEN } \Delta ndg = \text{S} \\
\textbf{IF } \Delta n_1 = \text{S } \textbf{AND } \Delta n_2 = \text{M } \textbf{AND } \Delta n_3 = \text{M } \textbf{AND } \Delta n_1 = \text{M } \textbf{THEN } \Delta ndg = \text{M}
\end{array} \quad (16)$$

The analysis of the rules also made it possible to identify those maturity capsules that are becoming necessary to be able to identify those cities where digital transformation processes are fast, and those cases of digital transformation that are very slow. The basis for such an assessment was not only the aggregated measure of the negentropy increments of the digital transformation maturity capsule, but also its components. Therefore, considering the developed detailed description of the constituent maturity capsules and their negentropy, an appropriate scenario can be selected to ensure a continuous increase in digital transformation.

On the one hand, the preparation of such a scenario becomes possible with the use of semantic analysis considering the adopted measures of excesses, but also considers expert assessments of the significance of this scenario for the city. In turn, the second of the verification processes listed above was carried out in the following stages:

- Identification of energy maturity capsules for digital transformation processes.

- Assignment of primary, secondary and scalar negentropy to these capsules.
- Analysis of maturity capsules from the point of view of building the rules of negentropy flow.
- Building flow model rules for the city.
- Relating the rules of the flow model for a city to the generic flow model for Smart Cities.

The basis for the verification process in this case were meetings with residents and employees of the City Hall, for whom the city's information architecture is a priority. The documents for the construction of the digital transformation policy were also the basis for verification, as well as the digital transformation policy itself addressed to residents. Based on these documents and meetings with residents, in the first stage, pre-processing processes were carried out, determining the linguistic rules for the process of building a digital transformation policy. The knowledge gained during meetings and documents allowed for:

- Identification of three out of four maturity capsules. It turned out that the capsule could not be identified.
- These capsules have been assigned the following negentropy values.

During the meetings, it was relatively difficult to identify the capsules and indicate their meaning. During these meetings, however, the need to define key components of maturity capsules was discussed, such as digital transformation, digital maturity of citizens, directions, values and principles of digital transformation policy. Therefore, at the meetings, the model of the negentropy flow was not seen, but its components. Hence, the unidentified capsules were focused only on the components. The next step in the verification process was the assignment of negentropy to individual components. In this case, the extreme values of negentropy from 1 to 5 were repeatedly indicated, indicating a small or very significant share of a specific process. It was much more difficult to define intermediate values, hence the estimation of negentropy and the increase of negentropy requires some knowledge and experience.

The introduction of the concepts of negentropy, primary, vector, and scalar primary, secondary, and tertiary, respectively, indicated the need for complexity in the evaluation process rather than explaining the meaning of each concept. Hence, it can be concluded that it is advisable to prepare experts for scalar assessment by identifying negentropy and its concepts.

The next step was to build rules based on the city based on the rules of the model developed in the work. In this case, the flow of processes was more readable for recipients than its implementation in the form of rules. When talking about the policy of digital transformation or when pointing to the needs of assessing the maturity of the city, awareness of these processes was less important than their sequence. Therefore, during these meetings attention was paid and many times discussed which of the processes is preceding for the next one and which in turn is the successor of the process that should be initially estimated.

The next step was to build rules. While it was relatively easy to identify processes and assign values to them, the rule-building stage turned out to be too complex. It also seems that in this case it is necessary to define a certain minimum maturity for implementing the proposed model. Hence, it seems that based on the verification process, it can be concluded that this model will be useful for IT organizations of city offices with a certain level of maturity.

The verification processes did not refer to the flow model because it was created, and it seems that looking at the problems related to both the identification of negentropy and the negentropy flow, this stage is premature for the application of the model for the city we are examining.

The verification process also showed how easy it is to define linguistic values and how much more difficult it is to define rules. Therefore, in order to build rules, the five-point scale proposed in the article was replaced with a three-valued scale in the verification processes. Assuming linguistic values at the level of three was definitely simpler than showing the value of negentropy from the point of view of five values.

Therefore, it should be considered to what extent the number of rules of the proposed model is adequate to the maturity of the organization of the city hall and the knowledge about the transformation processes. It seems that in the case of another city, it would be worth using a simpler model, identifying fewer linguistic values, building simpler rules and then trying to develop it.

Contacts with residents, but most of all contacts with the city office, showed that both residents and officials very easily define the components of maturity capsules at the level of two values. It is much more difficult to enter intermediate values, while the use of five linguistic values seems very difficult.

Nevertheless, the presented example of building a digital transformation policy for Warsaw has shown that it is purposeful to include linguistic values in the processes of building values and principles for the city's digital transformation policy. Therefore, if this model is used in other cities (such talks are currently underway), a change from the approach used in Warsaw to the incremental approach should be considered. In an incremental approach, the number of values and the number of rules will grow with the maturity of the evaluators and residents for whom the digital transformation policy is being built.

6. Discussion and Conclusions

The article discusses the possibility of using the rule-based model of negentropy to increase the energy efficiency of the city's digital transformation processes into a Smart City. Digital transformation is a very complex management problem that requires the use of appropriate methods of estimating their complexity in accordance with the Zadeh rule. Therefore, the authors of the article deviated from the conventional approach, in which process measures are key performance indicators. It seemed to them that such a description was too flat and does not reflect the complexity of these processes.

This new approach presented in the article is based on:

- Rule-based description of the state of digital transformation processes enabling their energy assessment;
- Introducing energy maturity capsules to describe the state of these processes;
- Application of measures based on project negentropy increments for maturity capsules.

Therefore, on the one hand, they introduced a process description for the evaluation of digital transformation processes, and on the other hand, they introduced energy maturity capsules for this process description. Then, for the maturity capsules, linguistic measures based on project negentropy increments.

Such a complex structure, but it seems to be adequate to the complexity of digital transformation processes, is the basis of research. It considers both Smart Cities processes for the city described in the first part of the work. It also considers the processes related to the assessment of the city's maturity to implement digital transformation projects. It also shows the processes of building a digital transformation policy and monitoring the state of these processes with the use of information architecture.

Energy maturity capsules are defined for this process description. The energy maturity capsule is a spatial measure of the author-designed processes represented by primary (spatial), secondary (vector) and tertiary scalar negentropy. To simplify the meaning of negentropy, the authors proposed an incremental approach in which the increase in negentropy indicates whether the digital transformation process is progressing or decreasing. It is based on these data that we are able to estimate the changes taking place in the city. The structure of the energy maturity capsules shows that from the thermodynamic point of view, when the external system is activated in a city, entropy decreases. It is a consequence of contact with the city's external systems described by the energy variables of the maturity capsules.

For the RMFDN model defined in this way, its implementation in the form of semantic rules preceded by pre-processing processes appropriately adjusted to the three levels of negentropy was assumed. The developed RMFDN model was verified in one of the European capitals by carrying out a sequential verification process. On the one hand, it included the selection of experts allowing us to determine the increments appropriate for a given process. It also enabled the construction of language scenarios based on increments and the construction of city development scenarios based on cases of city development described by maturity capsules.

The application of the model also showed how it is possible to use negentropy to estimate the processes of digital transformation and thus to indicate the processes which increase its state. If we assume the assumption of this work that the processes of negentropy are aimed at achieving the state of equilibrium of the city striving for Smart Cities and thus increasing the effectiveness of digital transformation processes, the created rule model allows for the analysis of these processes and their impact on the growth of negentropy.

It also seems that the next step in conducting research should be the use of a fuzzy description, in which the measures represented by negentropy can be related to the construction of fuzzy sets and membership functions. Therefore, it becomes necessary to prepare such digital transformation projects of cities in which we will not only introduce the concept of negentropy for the state of processes, but also adopt their measures. Those proposed in the study are pilot projects for a selected city. Therefore, we believe that in the presented article we have managed to change the visions of measures of digital transformation processes into thermodynamic ones, providing the basis for both the verification of quantitative measures and quantitative estimation of the energy efficiency of digital transformation processes.

In the case of building fuzzy energy models of digital transformation processes in cities, one should also take into account the limitations related to the use of these models, mainly related to the possibility of access to acute assessments using the existing linguistic measures. The conducted research related to the construction of the digital transformation policy shows that it is relatively easy to identify linguistic measures of processes and it is relatively difficult to identify sharp measures. Therefore, it seems that the subsequent stages of the research should enable the identification of possible and existing measures that could be introduced into fuzzy modeling.

Another limitation seems to be the selection of experts so necessary to build the proposed fuzzy model. The construction of a digital transformation policy has shown that the number of experts treating design processes in terms of energy is relatively small. Most experts are convinced that building a digital transformation policy and analyzing their processes is the use of key performance indicators. Therefore, it should be considered to what extent the construction of a fuzzy model should be preceded by a preliminary analysis of a new approach to the state of assessment of the design process, which is negentropy. It also seems that at this stage of the research, it is necessary to evaluate the possibility of using the model proposed in the work for other European cities, assess the state of experts and the possibility of treating design processes differently, and only then implement fuzzy modeling. However, it should be taken into account that the use of fuzzy modeling will allow for quantitative estimation of design processes that are so important in building the digital transformation of cities.

Author Contributions: Conceptualization, C.O.; methodology, P.C.; writing—original draft preparation, C.O.; writing—review and editing, P.C. and A.O.; project administration, A.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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