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Designing aggregate KPIs as a method of implementing decision-making processes in the management of Smart Cities

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Abstract

The aim of the paper is to present a concept of measuring the performance of city management processes by use of a concept of aggregate KPIs. In the management of organizations and, as a consequence of the use of a common design framework also in the management of cities, silo KPIs are commonly used to show the statuses of the processes of organizations/cities. Thus the question arises as to what extent aggregate KPIs, as proposed in the paper, can be used in the management processes of smart cities in place of the silo ones typical for organizations. The work is divided into four main parts. The first presents the problems of managing smart cities to introduce the reader to the problems of measuring processes and the need for aggregated measurements. The second section discusses KPIs and their place and role in management processes. The third part contains a description of the model of aggregate KPIs to support measurements of the status of city processes. In the fourth section the developed model is verified, demonstrating its applicability for city management processes. The summary includes a recommendation for the use of aggregate KPIs in the city.

Keywords: smart cites, knowledge base, knowledge management, fuzzy logic, process modeling, decision support

1. Introduction

Modern cities now occupy just 2 percent of the earth's surface and are home to as many as 50 percent of the world's population. It is expected that by 2050 already 70 percent of mankind will live in cities. According to data from the Central Statistical Office in Poland, already today the number is about 60 percent [xx4]. In addition, the number of people migrating from an urban to a metropolitan area is steadily increasing. All this results in the management of large cities becoming a challenge of modern civilization. It is dependent on experience, competence and above all available resources within the agglomeration. In many cities, decision-makers are widely supported by information technology in the analysis of their decision-making processes [10].

Although in the context of different conditions of the functioning of cities and their development many approaches and concepts of city management can be seen, they are increasingly treated as manageable in the context of the application of intelligent processes to manage their operation. A Smart (or Smarter) City can be described as an idea the foundation of which is the implementation of these processes. There is no single agreed definition of a Smart City. It should be assumed that it is rather a vision based on two pillars - best management practices and opportunities to support city processes with broadly defined information technology [6].

The implementation of IT in any large organization is an undertaking for which at least three limitations should be determined: the scope of work, the schedule of the project and its budget. From the point of view of such a large and complicated structure as a city, what is particularly important is the scope of work that is desired by the recipient - the functionality of the city system. The management of such a structure must first and foremost require the functionalities to be systematized and described and the most important ones to be selected. The identification of key functionalities for system implementation may be problematic in the case of these processes, the implementation of which involves several entities of the city. Then, the implementation of IT solutions is not synchronised by particular entities at different levels of local government, leading to a high degree of fragmentation of the processes and systems of the city.

The authors set themselves the goal of designing and implementing the system in Gdansk. It was assumed that the aim will be to design the components of the IBM IOC (Intelligent Operating Centre) project framework, which can be used in the case of other cities [xx3]. This paper focuses on the design of one of the components - KPIs as a measure of the status of the city's decision-making processes.

2. Examples of city decision-making processes supported by silo KPIs

KPIs (Key Performance Indicators) are defined as measures of processes regarding the achievement of an organization's objectives. This concept appears most often in the context of financial data and acts as a signal to decision-makers about the status of work processes, their cost or quality. They may take the form of managerial control tools and should create conditions to make decisions without burdening decision-makers with a detailed analysis of the source data. In practice, many different KPIs are defined for business use: financial indicators (e.g. the margin calculated per customer, the sales value calculated per employee), in the customer service area (% of overdue deliveries to customers), quality of service (number of complaints) and many more [xx8]. It should be noted that a KPI is a function of any input data which is relevant in terms of the decisions taken. What is important in the context is the scale predetermined for each indicator identifying critical values (the exceeding of which should be treated as an emergency situation) [7].

KPIs are an element of most information systems, which assist the management of the organization at various levels (operational to strategic). They are implemented in systems such as ERP (Enterprise Resource Planning) or CRM (Customer Relationship Management). They are also used in the systems of Smart Cities. In such systems, the structure of KPIs covers the following sequence of processes:

- the identification of external data sources feeding the internal database of the system of Smart Cities (including - establishing timetables for their acquisition),
- the construction of KPI models that define relationships between different input data (one KPI model can be used to build a family of a number of KPIs),
- the development and definition of individual KPIs, which will be available on the desktop of the system operator (including setting the scale presented by the system through a range of several colors).

The above-described sequence of processes leads to the running of cyclic data flow in the systems of Smart Cities. This sequence is illustrated in Figure 1. The source data is obtained from external sources which supply the internal database of Smart Cities (process 1). Figure 1 shows a sample database implementation for the IBM IOC system. This database itself is a source of data for KPI models (process 2). KPI models represent logically (thematically) grouped data for the needs of specific KPIs (process 3). Each defined KPI becomes an object accessible to the operator from his desktop. The operator, however - from the point of view of decision-making processes, becomes a "KPI watcher", and only then - a decision-maker [1].

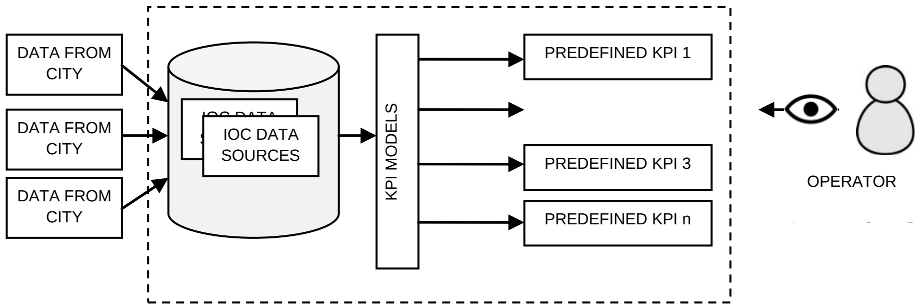


Fig.1. Systems of Smart Cities - sequence of KPI design processes

The above-described indicator design process is an example of the design of so-called silo KPIs. They work well for the implementation of procedures that do not require immediate action. Much of the data may in fact be obtained from the city with a delay with respect to measurements. Many measurements are not made in a continuous cycle, so the operator does not receive them in the system in real time (e.g. meteorological measurements from sensors). Such an approach is acceptable only for a part of the city procedures. In the event of an incident posing a threat to human health and life, the effectiveness of the relevant services coordinated by the operator directly depends on the speed of obtaining data. Then support for decisions is understood as the following sequence of processes:

- immediately providing the operator with information about the existence of the threat (by launching the KPIs),
- supporting the operator in the rapid notification of the relevant services (in accordance with the obligation that in a given crisis situation is imposed on the city by a proper act of law),
- presenting options and suggestions for decision-making processes - in particular, the allocation of resources such as ambulances, the fire brigade, etc.

In the cases described above, a KPI is a source of information (knowledge) related to a specific single critical situation, which is easy to model. The system designer in the creation of a model of a silo KPI needs specific (key for the process) data from external sources, an established method of data processing and the determination of an item on his desktop along with the presentation conditions of this element (the scale and limit values). However, if we assume that in an organization like a city every day many emergencies occur simultaneously, then it is a decision-making problem for the operator when he receives e.g. two alerts (emergency notifications). He must then run two parallel procedures, with the result that at the system level, there is a need to integrate data from external sources which are unrelated. In the absence of such integration, decision support must be implemented through many different KPIs. An example diagram of the actions of an operator caused by two simultaneous KPI alerts is shown in Fig. 2.

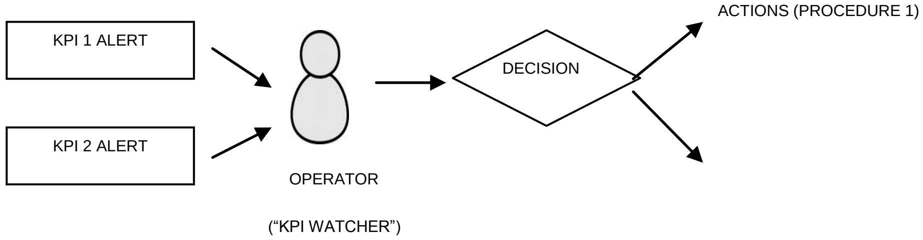


Fig.2. Diagram of operator actions caused by two simultaneous KPI alerts

Figure 2 presents a situation in which the operator should make a decision (the allocation of resources available in a limited amount) for two emergencies signaled by two different KPIs. These two data sources, disjointed for the operator, mean that he must perform an aggregation of both KPIs. Such a solution is a heavy burden for the operator and at the same time increases the uncertainty of decision-making. However, based on an analysis of the situation shown in Figure 2 the following conclusions can be formulated regarding the impact of a KPI analysis on the decision-making processes of an organization (in particular - a city):

- a KPI, understood as a system interface element indicating a critical situation on the basis of simple arithmetic, takes the form of a silo [xx2]. It acts as an alert to the operator, but by itself does not support his decision. In situations where there is a real threat to human life, this solution is therefore too "slow".
- KPIs are tracked individually by the operator. A KPI performs a separate calculation of an incoming value in relation to the threshold value; similarly each indicator is displayed as a separate object. A screen with multiple KPIs available to the operator may cease to be legible (see Fig. 3, which shows an example of a system desktop with several KPIs defined).
- KPIs can thus be identified with so-called information silos - being an accurate view, but only of a slice of the critical area of the city.

The above observations are well illustrated in Figure 3, which is a screenshot of the IBM IOC desktop. It shows the silo KPIs as a set of elements (rectangles) regarding three different situations: the emergency landing of an airplane, exceeding PM10 and the use of ambulances. The color range is set at the construction stage of the KPIs.

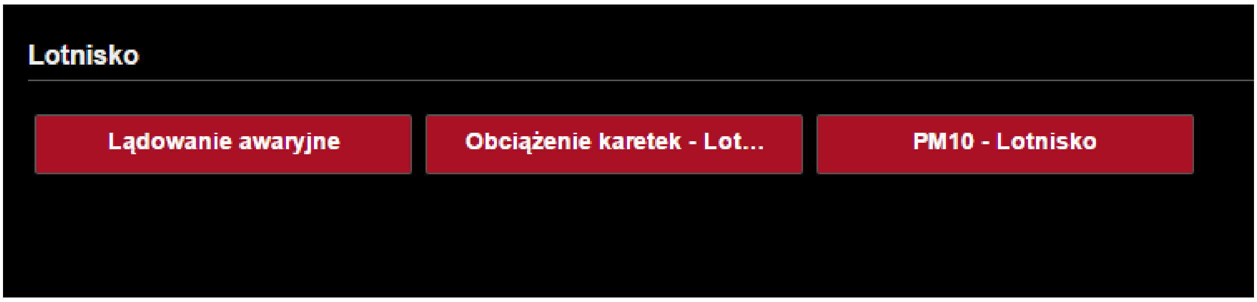


Fig.3. Silo KPIs of the IOC system for the emergency landing of an aircraft, exceeding PM10 and the use of ambulances

The above-mentioned KPIs represent status images of information silos and do not depend on each other. They illustrate the statuses of processes, but in a detached way. However, in such an organization as a city, the city processes are closely dependent on each other, so the idea of the presented KPIs is not fully reflected in the city from an analysis of the status of city processes [xx9]. Therefore, the aim of this work is to present aggregate KPIs which fully, not in part, will be used in city decision-making processes. They should be used by the operator/decision maker and their design should be based on models of city processes. The model of aggregate KPIs is discussed in the next section of this paper.

3. Models of aggregate KPIs

In the previous section silo KPIs based on individual data were defined at the implementation stage of the Smart Cities system. Currently, the concept of integrated KPIs will be presented based mainly on models of the city processes, which form a basis for creating logical chains of KPIs designed in a Business Monitor. This type of KPI is used to create dynamic structures to support decision-making processes. A generic model of these indicators was developed for the implementation of decision-making processes for any city.

3.1 Aggregate KPIs - definition and meaning

The silo KPIs which were presented in the previous section of this paper are subject to procedures for processing data in information silos. Unlike them, aggregate KPIs are structures which operate further in a specific context of decision-making - being the currently implemented decision-making processes of the city (activating specific operating procedures). The launching of aggregate KPIs is determinant to a certain, specific procedure, which constitutes a response to a detected threat (real or potential).

To further explain the concept of aggregate KPIs, it is necessary to clarify important concepts. The paper considers aggregate KPIs as a sequence of processes, which include:
Decisions - as a consequence of choices faced by the operator; they affect the processes of the city
Actions - which depend on the decisions taken and are seen as consequences of the decisions and are depicted as results of KPIs which:

- induce procedures (hereinafter referred to as initiating KPIs - KPI_I) - exceeding the critical values presented by them makes the first step in each of the procedures. Examples of KPI_I: exceeding the safe levels of airborne concentrations of air pollutants (e.g. PM10).
- provide information helpful in decision-making (called supporting KPIs - KPI_W) and are necessary in the decision-making process. In the studied cases KPI_W was identified with the number of available resources necessary to reduce or eliminate the emergency. Examples of KPI_W: the number of available ambulances in the city, the number of beds in public medical facilities.

Example initiating KPIs (emergency landing and exceeding PM10 levels) and supporting KPIs (number of ambulances) are presented in Figure 4.

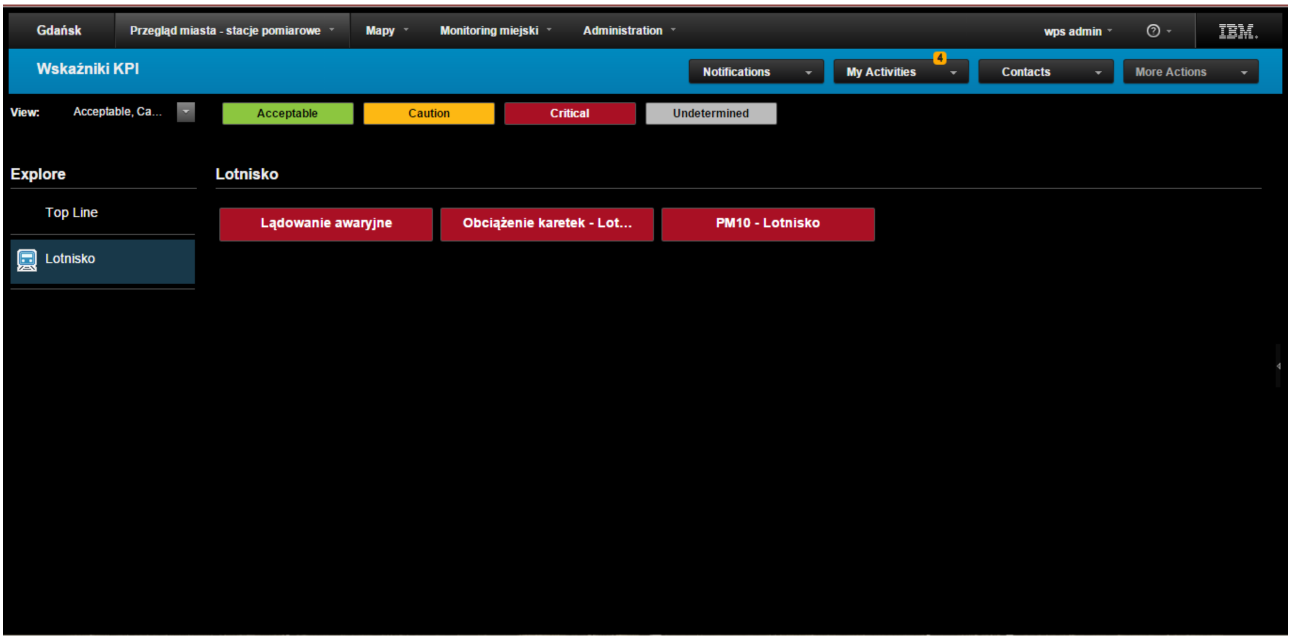


Fig. 4 Initiating and supporting KPIs as components of aggregate KPIs

The following presents the structure of a decision-making chain showing how aggregate KPIs are constructed (Formula 1)

```
if (Lądowanie_x0020_awaryjne>=70 and PM10_x0020_-_x0020_Lotnisko>=60) then 2
else if (Lądowanie_x0020_awaryjne>=70 and PM10_x0020_-_x0020_Lotnisko>=30) then 2
else if (Lądowanie_x0020_awaryjne>=70 and PM10_x0020_-_x0020_Lotnisko>=0) then 1
else if (Lądowanie_x0020_awaryjne>=40 and PM10_x0020_-_x0020_Lotnisko>=60) then 1
else if (Lądowanie_x0020_awaryjne>=40 and PM10_x0020_-_x0020_Lotnisko>=30) then 1
else if (Lądowanie_x0020_awaryjne>=40 and PM10_x0020_-_x0020_Lotnisko>=0) then 1
else if (Lądowanie_x0020_awaryjne>=0 and PM10_x0020_-_x0020_Lotnisko>=0) then 0
else if (Lądowanie_x0020_awaryjne>=0 and PM10_x0020_-_x0020_Lotnisko>=1) then 0
else 0                                                                    (1)
```

It covers both the procedures (described above) as well as taking into account the levels of risk. The condition for the recognition of a situation as dangerous and the launching of the due process in this respect is the case of only one initiating KPI (KPI_I) exceeding (e.g. the level of PM10). It is enough to receive a signal that the KPI values have been exceeded to recognize a situation as dangerous. In the above procedure (Formula 1) it becomes necessary to acquire the values of many supporting KPIs (KPI_W). The model of the relationship between various types of KPI and the procedure of conduct, which is a generalization of the processes shown in Figures 3 and 4, is shown in Figure 5. In this Figure, the axis representing performance during the procedure to be conducted presents initiating KPIs (at the beginning - this indicator starts a sequence of actions) and supporting KPIs (during the procedure - when making decisions).

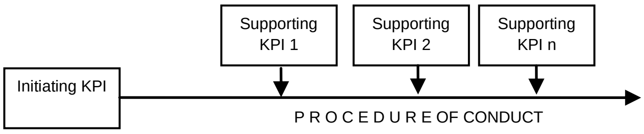


Fig.5. Model of relationships between initiating KPIs and supporting KPIs and the procedure of conduct developed on the basis of Fig. 3 and 4

In the case of a single threat silo KPIs still seem to be sufficient - both in the role of initiating and supporting. A silo KPI does not require the context of the processes mentioned above, it is always launched in connection with one particular decision-making process. However, it should be noted that in the case of a simultaneous occurrence of two (or more) threats the simple operational model becomes inefficient, and in fact, almost impossible to use. The operator receives two different suggestions of decisions on the allocation of resources (e.g. the mentioned ambulances) from two different procedures in the system. Unfortunately, neither of the procedures takes into account the existence of the other. In extreme cases, it may be that for both threats the operator will be prompted to allocate the maximum available resources (i.e. for example sending all available ambulances to two different places). The decision support model for the two processes supported by silo KPIs is shown in Figure 6.

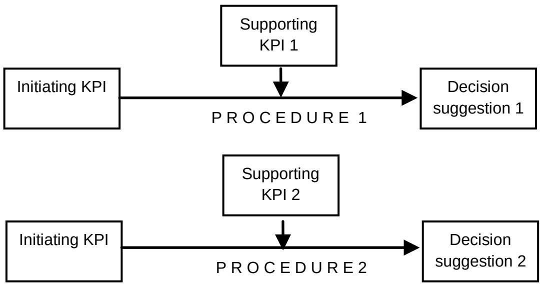
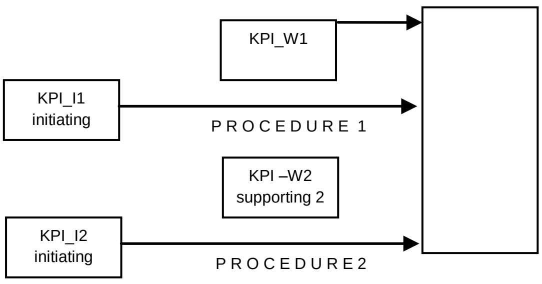


Fig.6. Model of support for two simultaneously launched procedures by silo KPIs - two independent decision suggestions

The solution for the problem presented in Figure 6 is a decision support model that uses aggregate indicators. Their essence and meaning will be described in the next section.

3.2. Model of aggregate KPIs in support of city procedures

The most important premise at the basis of the structure of this model is the elimination of independent decisions, being a consequence of the applied procedures. It is assumed that procedures that the operator coordinates cannot be considered separately because there are common factors of both decisions pictured by the aggregate indicator (KPI_Z). KPI_Z will present the state of data taking account of many city processes varied as to value and size. The functioning of aggregate KPIs is shown in Figure 7.



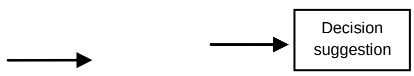


Fig.7. The proposed city decision support model for several simultaneously launched procedures integrated through the aggregate KPI_Z

Hence, the models presented in Figures 6 and 7, although based on the same initial assumptions, generate two different types of decision suggestions (two independent or one cumulative), because:

- The operator, in both cases, faces two notifications (initiating KPIs).
- The operator uses two simultaneous decision suggestions (using two supporting KPIs).

The cumulative decision is the result of the aggregation of initiating and supporting KPIs. They form the integrated KPI_Z. As previously assumed, decision support is understood here as the separation by the operator of scarce resources needed to implement the accepted procedures (Fig. 7). Any procedure which is a response to a critical situation in the city can be seen as a pair of (two) elements described as:

$$P_x\ [KPI\_I_{1x}, (KPI\_W_{1x}, KPI\_W_{2x}, \dots, KPI\_W_{nx}\ )\ ] \qquad (2)$$

where:

Px – procedure X
KPI_I_{1x} - KPI initiating procedure P_X
KPI_W_{nx} - KPI set to support procedure P_X

It should be noted that in different procedures the same KPI_W (supporting) may be used. Hence, the first step in the stages of the implementation of Smart Cities can be the preparation of a KPI_W directory. In this way, the aggregate indicator KPI_Z will be able to use an identical KPI_W for two analyzed procedures. This approach creates conditions for the allocation of the same kind of resources (e.g. both procedures require information on the number of ambulances, so for both, a decision must be taken concerning the same resources). Such a catalog of KPIs can provide a basis for the ontological description of KPIs.

The proposed aggregate indicator KPI_Z will therefore present the value (result) dependent on the status of the indicators initiating all the procedures P_x that are being initiated at a given time. The process of formalizing indicators and procedures defined in such a way creates conditions for the integration of all the threats that exist at the same time and require decisions concerning the allocation of resources. The aggregate KPI_Z is therefore a function dependent on the procedures P_1, P_2,… P_n that it integrates. Thus, the KPI_Z indicator for a particular procedure Px will adopt a value which depends on the number of resources that can be allocated to the procedure x.

$$KPI\_Z = f(P_1, P_2, \dots, P_n) \qquad (3)$$

It is important to clarify on what basis the KPI_Z indicator will adopt certain values. These values may be adopted at the stage of the modeling and implementation of each procedure with the use of a so-called KPI dependence matrix and during the updating of the priorities matrix. Both of these matrices form a knowledge base to complement the processes of modeling.

3.3. Dependence matrices of aggregate KPIs

KPI dependence matrices are objects that inherently contain knowledge about relationships between various indicators which a given procedure uses. Thanks to their creation, a KPI designer will directly identify connections between KPIs and city processes. This dependence becomes essential for the proper utilization of the KPI_Z indicator. Therefore, in building a dependence matrix for each procedure, it will be necessary to determine which KPI_I and which KPI_W are necessary for the proper operation of aggregate KPIs. An example KPI dependence matrix is shown in Table 1.

	KPI_I_1	KPI_I_2	KPI_I_m
KPI_W_1	Z_{11}	Z_{21}	Z_{m1}
KPI_W_2	Z_{12}	Z_{22}	Z_{m2}
KPI_W_n	Z_{1n}	Z_{2n}	Z_{mn}

Tab.1. Dependence matrix KPI_I - KPI_W for a single procedure

It is also assumed that:

$$Z_{XY} \in \{0,1\} \tag{4}$$

where:

Z_{XY} - a relationship between procedures X and Y expressed in a binary way;

A value of 0 indicates no correlation in the given procedure between KPI_I and KPI_W indicators while a value of 1 means that such a correlation exists. A threshold of acceptability of the value of this factor is not specified.

The KPI dependence matrix described in this section is designed to link existing indicators of different procedures. The system will then be able to use that knowledge at the stage of checking to what extent two critical situations require the same kind of resources to be allocated. If it turns out that such a requirement exists, the operator will face a decision concerning the allocation of a specific number of resources to be directed to two different locations in the city. To determine which resources are of higher priority it becomes necessary to construct a priorities matrix. The method of its construction is detailed in the next section.

3.4. Priorities matrix of aggregate KPIs

If it turns out that there is a need to make a decision on the allocation of resources of the same type, it should be determined which part of the resources should be assigned to which procedure. Therefore it becomes necessary to define the rules for the determination of the KPI_Z indicator for each of the procedures. At the implementation stage of the procedure, the priority must be specified with regard to other procedures. Such knowledge is stored in the priorities matrix (Table 2).

At this stage it is assumed that for each procedure P_x a weight relative to all other procedures will be specified. It is a simplified assumption that certain critical situations will arbitrarily have a higher priority than others at the resource allocation phase.

	P_1	P_2	P_n
P_1	0	W_{12}	W_{1n}
P_2	W_{21}	0	W_{2n}

P_n	W_{n1}	W_{n2}	0

Tab.2. The priorities matrix for procedures running simultaneously

The W_{XY} values included in the table represent the priority of procedure X with regard to procedure Y. It is also assumed that the following conditions must be met:

$$W_{XY} > 0, \ gdy\ X <> Y$$
(5)

$$W_{XY} = 0, \ gdy\ X \leq Y$$
(6)

$$W_{XY} = \frac{1}{W_{YX}}$$
(7)

It is also assumed that the value of W_{XY} is important and used to calculate the KPI_Z, where at the same time two premises occur:

Both procedures X and Y are launched simultaneously.
Both procedures X and Y use the same KPI_W indicators (i.e. require resources of the same type).

The value searched for an aggregate KPI_Z indicator for procedure X will then be determined as follows:

$$KPI\_Z_X(P_X) = W_{XY} * KPI\_W_n \quad (8)$$

The indicator calculated according to the Formula (8) uses both pre-defined KPIs and knowledge contained in both KPI matrices - dependence and priorities. It should be emphasized that the presented method of determining the indicators should be verified. For the purposes of this process, the occurrence in the city of two different threats was assumed and it was shown how the aggregate KPI_Z indicator can be applied in this case to support the decision maker - the operator of the Smart Cities system.

4. The use of the aggregate KPI model in the process of designing the Smart Cities system

In order to verify the model presented in this study, we analyzed the potential situation of the simultaneous occurrence of two threats of a different nature. Despite the differences, both cases may pose a real threat to the residents of the city and both are defined in the city procedures of conduct. The following two procedures were considered:

- Procedure P_1: launched, if it is found that the concentration of hazardous substances in the air (in particular - PM10) has exceeded a level safe for residents - the appropriate KPI_I_1 is triggered when one of the measuring stations (sensors) located in the city provides a series of data regarding the concentration of PM10 higher than the established threshold; such a situation may adversely affect the well-being and health of the residents located in the area covered by the event. Recommended actions/decisions for the operator: to proactively send ambulances to the site.

- Procedure P_2: when a signal is received from airport services concerning problems with an airliner approaching for landing (KPI_I_2 launched); passenger lives in danger. Recommended actions/decisions for the operator: to proactively send ambulances to the airport (just as in procedure P_1).

The decision problem for the operator is therefore to select the adequate number of ambulances to be sent to each place. For such a simplified example the following variables will thus be specified, expressed in the IBM IOC system with KPIs:

- KPI_Z_1 and KPI_Z_2 - searched values - the number of ambulances suggested to be sent respectively for procedures P_1 and P_2,
- KPI_I_1 - the indicator initiating procedure P_1, i.e. exceeding the permissible concentration level of PM10,
- KPI_I_2 - the indicator initiating procedure P_2, i.e. information about danger to the aircraft,
- KPI_W_1 - the number of ambulances available at a given time, information acquired from the medical services. For this example, it is assumed that KPI_W_1 = 100.

As both procedures use the same KPI_W indicator, the dependence matrix Z between KPIs looks like that shown in Table 3.

	KPI_I_1	**KPI_I_2**
KPI_W_1	1	1

Tab. 3. Dependence matrix Z for the test case

For this case it is assumed that procedure P_1 has a much higher priority than procedure P_2 in terms of the resource allocation.

	P_1	**P_2**
P_1	0	0,25
P_2	4	0

Tab. 4. Dependence matrix W for the test case

On the basis of data available in real-time and matrices prepared in the modeling and implementation stage, the system calculates the value of the aggregate indicator:

$$KPI_{Z_1(P_1)} = 0,25 * 100 = 25 \quad (9)$$

(suggested number of ambulances for P_1)

$$KPI_{Z_2}(P_2) = (1 - 0,25) * 100 = 75 \quad (10)$$

(suggested number of ambulances for P_2)

The above calculations for KPI_Z support the decision-making process for the allocation of resources. They represent suggestions to the operator regarding the allocation of resources.

5. Summary

The paper focuses on the current issues of the use of KPIs as mechanisms to support the management of an intelligent urban agglomeration (Smart City). The work was based on conclusions pointing at the shortcomings of simple KPIs, built-in as standard in many information systems that support decisions. Such indicators are independent of each other. Thus they constitute information silos.

The quality of decisions taken in any organization - also in a city - depends on the data available to decision-makers and the context of their use. In the studied case such a context are the processes of the city and every decision has to be taken with regard to their conditions and limitations. In the silo KPI approach, however, such context does not exist. The decision support model proposed in this paper is the answer to this problem. It introduces KPI_Z mechanisms, or aggregate KPIs. Such indicators should be defined in the context of all procedures, by which data critical to the decision maker is aggregated. The data that the model takes into account during the calculation of such an integrated context are associated with each procedure by initiating (KPI_I) and supporting (KPI_W) indicators and the matrices described in the previous section.

The presented model is a simplification. It assumes only those situations where two phenomena occur simultaneously generating potential conflict regarding resources. Hence a two-dimensional priorities matrix is proposed. Anticipating the need to simultaneously launch *n* procedures, this matrix would need to be given *n* dimensions. This complication, however, forces the expert team to identify and develop a much larger number of dependencies between processes. But this raises similar concerns to be faced by a knowledge engineer in the search for knowledge - should the knowledge base be complete (such a goal is time-consuming and difficult)? Perhaps, conversely, it should contain only knowledge sufficient to make most decisions (but easier to save)?

These questions result in another goal of research for the authors. That is an extension in the model of the possibilities offered by the dependence and priorities matrices. In the presented concepts they contain numerical values that indicate the strength of relationships between KPI_I and KPI_W indicators respectively and the procedures P themselves. These relationships in complex organizations, however, might not be described so clearly. Therefore, the model should give the possibility to include certain conditions in the matrices beyond the numerical values themselves. These conditions are simple IF-THEN decision rules (implications), which the authors are planning to include in the model as elements influencing the results generated by the aggregate KPI_Z.

Aggregate KPI_Z indicators should be applied in any organization where the number of operating processes is large and at the same time they are linked together with the resources necessary to implement them. The above plans to develop the model are a response to such a need. At the same time, they illustrate the complexity of the problems of managing a Smart City as seen through the prism of the city processes.

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