UNIVERSITY OF LATVIA

AIVARS NIEDRĪTIS

ARCHITECTURE FOR MULTI-TENANT ADAPTIVE INFORMATION SYSTEMS

SUMMARY OF DOCTORAL THESIS

In Partial Fulfillment of the Requirements
of the Doctor Degree in Computer Science
Subdiscipline of Data Processing Systems and Computer Networks

R ī g a - 2013

University of Latvia

Faculty of Computing

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Abstract

The architecture of a multi-tenant adaptive web-based information system is proposed, which employs the idea of using software as a service. The architecture is applicable to systems that are in use in many organizations; however, the functionality on the organizational level and individual user level is different. The architecture provides an option for users to take advantage of the functionality of multiple organizations simultaneously or sequentially.

The adaptation process is based on a comprehensive user model, which includes various aspects to describe a user.

The architecture also includes the action collection and analysis component that is employed in process measurement. A metamodel to describe performance indicators is proposed as well as performance measurement framework. Business performance measurement is presented in two levels of measurement: system-level measurement and business process measurement.

The architecture has been tested in two projects – information systems employed in the University of Latvia and other institutes of higher education, and vehicle register employed in the Road Safety Department and related organizations.

Keywords: web-based information system, software as a service, information system architecture, adaptation

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1. GENERAL DESCRIPTION OF THE THESIS

Software as a service (SaaS) is a new way of delivering applications based on Internet technologies. SaaS application is always available, when a user has Internet access. In accordance with his needs, the user (or organization) chooses a SaaS application and leases this software service.

In the case of a SaaS application, it is strictly separated that the owner of the software is the service provider who deploys the application on his resources but the tenant can use the software accessing this service through Internet (Laplante et al., 2008). For SaaS applications the following issue becomes topical: how to adapt the same application in case of multiple users to somewhat different and specific for the needs of a certain user, because it is unlikely that business processes will be identical in two organizations that are planning to use the SaaS application.

The issues concerning the configuration are becoming topical, and in this regard are reviewed also the issues of software architecture to understand how a configurable SaaS application can be specified (Laplante et al., 2008).

For SaaS applications it is also essential to ensure data isolation for each of multiple tenants. The SaaS approach should guarantee that different tenants in case of one physical instance of the software will get applications appropriate for their business.

1.1. Topicality and Novelty of the Theme

The author's experience in development of Web Information Systems (WIS) is reflected in many papers and presentations in specialized conferences about information systems (IS) for higher education (Stonis et al., 2001), (Niedritis, Niedrite, 2000), (Niedritis, 1999), (Niedritis, Niedrite, 1998). From the occurrence of the IS for universities it was developed as WIS, although in the beginning the information system (LUIS) was built only for the University of Latvia. Later this system was broadened for the needs of several universities; the development of LAIS (IS for universities in Latvia) was started on the basis of LUIS. The experience gained during LAIS development allowed to conclude what problems occur in the process of development and maintenance of such WIS (Niedrite, Niedritis, 2003), (Niedritis et al., 2007). Financing for LAIS was granted only for development, but for maintenance the financial and human resources were limited, so it was necessary to create a new architecture suitable for development of an adaptive WIS that could be easily maintained and extended as well as adapted for individual needs of different users.

Different architectures for development of the information systems are described in the literature and widely used in the practice. To support the users with an appropriate web information system (WIS), a special attention was payed to the development of cost effective and flexible systems, and also to the Software as a Service (SaaS) approach. At the same time, to ensure effective WIS usage by the evaluation of system usage for the business process support, it was necessary to find and analyze the existing methods for the business process and performance measurement.

The novelty of the architecture that is based on Software as a service approach and that is proposed in the Thesis is defined by following aspects:

1) unlike the existing solutions, that for the adjustment of SaaS based information systems use configuration based methods, the architecture proposed in the Thesis is based on two level adaptation approach, that is characterized by following new features:

- it ensures different WIS instances for each organization, that is a tenant of the developed WIS, by adjusting these instances to the organization's functionality,
- it ensures an adapted WIS instance for each individual user based on the user model, that allows dynamic generation of the user interface according to the performed actions by the user during the work,

- it ensures an integrated, adapted WIS user interface for the situation when an user is authorized to work simultaneously with WIS instances of more than one organization. So, the possibility is ensured for the user to work with all data in all WIS instances according to the user model.
- for the development of the user model a method is provided, which is based on integration of particular user models of all WIS instances. So, a possibility is ensured to generate an integrated user interface.

2) For the purposes of the WIS adaptation architecture a measurement framework and method is proposed, that is characterized by following new features:

- for the support of definition and control of measurement indicators a five step indicator life-cycle is proposed, that ensures a systemic measurement process,
- the measurement system is based on data warehousing components by adjusting them to the analysis purposes of the SaaS based WIS performance to support the maintenance of multiple adapted WIS instances,
- two level measurement method ensures the determination of system usage practice to provide the results for the further development of WIS and payment evaluation for the usage of the systems.

The topicality of WIS development problems is determined also by the existence of several conferences devoted to these issues. For example, specialized conferences WISE *(Web Information Systems Engineering*), which in 2012 was organized at the 12th time, were fully devoted to the different issues about WIS development technologies, methods and applications. Other conferences include in their programs also topics concerning WIS development, for example, ICEIS (*International Conference on Enterprise Applications*), ISD (*Information Systems Development*) and many others.

At the same time the issues about business process measurement and reengineering, indicator determination and formal definition are topics that correspond to problems discussed in BIR (*Business Informatics Research*) conference.

1.2. The Goal and Tasks of the Thesis

The goal of the thesis is to develop architecture for development of web information systems (WIS) based on SaaS approach, which will ensure adaptation possibilities of WIS according to needs of individual users, usage of the WIS by several organizations, development and maintenance support.

The following tasks must be done to achieve this goal:

- A review of literature should be done and existing approaches in WIS adaptation explored,
- An analysis of literature to find out the existing approaches in configuration and adaptation of SaaS applications must be performed,
- A conceptual development of an architecture for SaaS approach based WIS development must be performed in a way that it will ensure adaptation possibilities of WIS according to needs of individual users,
- a support mechanism for maintenance and development of SaaS approach-based WIS must be prepared for the proposed architecture,
- The proposed architecture must be applied to the development of WIS.

1.3. Theses Formulated in the Research

The following theses were formulated in the Thesis: it is possible to perform effective development of web information systems based on innovative architecture which carries out the software as service approach.

The following research questions are investigated in the Thesis:

- Principles for formation of the architecture to support WIS adaptation for both tenants of the software service and individual users,

- The role and structure of the user model in the proposed adaptation architecture to implement an adapted SaaS application,
- Problems in usage of WIS implemented according to the proposed adaptation architecture – measurement, usage pattern analysis and evaluation.

1.4. Description of Methods

The theoretical research was based on literature review, analysis, summarization, and systematization to find out the existing solutions in the area of adaptive web information systems and to estimate the usage possibility of existing solutions in the case of specific types of WIS - SaaS approach based web information systems. In the Thesis modeling techniques are used for development of user model for proposed adaptation architecture as well as for modeling of the indicator model of measurement component of the adaptation architecture. These models are described by UML. Program engineering methods are used to develop the proposed architecture and implement two web information systems based on proposed adaptation architectures in two different projects.

1.5. Approbation of Thesis Results

Thesis results have been approbated in the Information System for the Universities, in the Vehicle Register of Road Traffic Safety Directorate, and at University of Latvia. Information System for the Universities is based on proposed Architecture for Multi-Tenant Adaptive Information Systems, and by November 2012 this system has been used by 13 tenants (universities). The Vehicle Register, which also was build according to the principles of proposed architecture, is used by 24 regional departments of Road Traffic Safety Directorate and by 36 external organizations. Two-level process measurement was fulfilled at the University of Latvia within the e-university project in year 2007.

The research was supported by ESF Project (Nr.2009/0216/1DP/1.1.1.2.0/09/APIA/VIAA/044)

The results of the Thesis are described in 10 scientific papers:

(Niedrite et al., 2007a) Niedrite, L., Solodovnikova, D., Treimanis, M., Niedritis, A. The Development Method for Process-Oriented Data Warehouse, In: WSEAS Transactions on Computer Research, Issue 2, Vol. 2, pp. 183 – 190 (2007)

(Medvedis et al., 2008) Medvedis, I., Niedrite, L., Niedritis, A., Treimanis, M., Voitkans, A. E-University Initiative: Approach, Solutions and Case Studies. In: Proceedings of the 8th International Baltic Conference on Databases and Information Systems, Estonia, pp. 141-152 (2008)

(Medvedis et al., 2008b) Medvedis, I., Niedrite, L., Niedritis, A., Treimanis, M.,Voitkans, A. Approach and Technical Solutions for e-University Initiative', Postconference proceedings of the 8th International Baltic Conference on Databases and Information Systems, Tallinn, Estonia, Frontiers in Artificial Intelligence and Applications by IOS Press, 2008.

(Niedritis, Niedrite, 2011) Niedritis, A., Niedrite L. The Adaptation of a Web Information System: a Perspective of Organizations, In: Pokorny, J. Repa, V., Richta K. et al. (Eds) Proceedings of the 19th International Conference on Information Systems Development (ISD2010), Springer, pp. 539- 550, (2011).

(Niedritis, 2011) Niedritis, A. Delivery of Consistent and Integrated User's Data within a Multi-Tenant Adaptive SaaS Application. In: Niedrite, L., Strazdina, R., Wangler B. (Eds.), Perspectives in Business Informatics Research. Local Proceedings of 10th International Conference, BIR2011 Associated Workshops and Doctoral Consortium, Riga Technical University, pp. 307-314, (2011)

(Niedritis et al., 2011a) Niedritis, A., Niedrite, L., Kozmina, N. Performance Measurement Framework with Formal Indicator Definitions. In: Grabis, J., Kirikova M. (Eds), Perspectives in Business Informatics Research, Lecture Notes in Business Information Processing, Volume 90, Springer, p. 44-58. (2011)

(Niedritis et al., 2011b) Niedritis, A., Niedrite, L., Kozmina, N. Integration Architecture of User Models. In: Niedrite, L., Strazdina, R., Wangler B. (Eds.), Perspectives in Business Informatics Research, Local Proceedings of 10th International Conference BIR2011 Associated Workshops and Doctoral Consortium, Riga Technical University, pp. 323 – 330. (2011)

(Niedritis, Niedrite, 2012) Niedritis, A, Niedrite, L. Adaptation of the Presentation in a Multi-tenant Web Information System, In: Skersys,T., Butleris R., Butkiene R. (Eds.), Information and Software Technologies, CCIS , Vol. 319, Springer, pp. 176 – 186 (2012).

(Niedritis et al., 2012) Niedritis, A., Niedrite, L., Zuters, J. Performance Measurement Framework with Indicator Life-cycle Support, In: A.Caplinskas, G.Dzemyda, A.Lupeikiene, O.Vasilecas (Eds.) Databases and Information Systems. Tenth International Baltic Conference on Databases and Information Systems. Local Proceedings, Materials of Doctoral Consortium. Vilnius, Žara, pp. 115-127, (2012).

(Solodovnikova et al., 2012) Solodovnikova, D, Niedrite, L., and Niedritis, A. Query-Driven Method for Improvement of Data Warehouse Conceptual Model, Proceedings of the 21st International Conference on Information Systems Development (ISD2012), Prato, Italy, Springer (in print).

The author has presented the work results at following scientific conferences:

- Baltic DB&IS conferences in year 2008 (Medvedis et al., 2008) and in year 2012 (Niedritis et al., 2012),
- ISD conferences in year 2010 (Niedritis, Niedrite, 2011) and in year 2012 (Solodovnikova et al., 2012),
- 68th scientific conference of University of Latvia, Information technology track, in year 2010, presentation A. Niedrītis, L. Niedrīte, M. Treimanis „Architecture of a business process measurement system",
- UOII Workshop of BIR conference in year 2011 (Niedritis, 2011),
- ICIST conference in year 2012 (Niedritis, Niedrite, 2012).

The author has reported about one of the systems used for approbation of the results of the research at the specialized EUNIS conferences (European Universities Information Systems):

- „Student and Employee Self Information/Registration Services", EUNIS2007, Grenoble, (Niedritis et al., 2007)
- "The Development and Implementation of Unified Information System for Universities in Latvia – a Retrospective View and Conclusions", EUNIS2003, Amsterdam (Niedrite, Niedritis, 2003),
- „Latvian University Information System security aspects in different application environments" EUNIS99, Espoo (Niedritis, 1999),
- "Latvian University Information System", EUNIS98, Prague, (Niedritis, Niedrite, 1998)

1.6. Thesis Volume

The Thesis contains 114 pages without appendices, 45 figures and 6 tables. The Thesis is organized in five chapters.

The first chapter (Introduction) defines the scope of the research, the choice of the research theme is justified and the main results of the research are described.

The second chapter defines the main concepts concerning web information systems that are relevant to the Thesis. The goal of this chapter is to give an overview about the existing architectures for web information systems.

The third chapter describes the proposed Architecture for Multi-Tenant Adaptive Information Systems. Basic principles, components and their features of the architecture are defined. In this chapter an example of how this architecture is used to develop one web information system is provided. The chapter also describes how the user interface is constructed for the WIS that is based on the proposed architecture in a specific situation, when one user uses more than one instances of this WIS simultaneously.

The fourth chapter proposes a method that constructs a use model based on the notion of user-describing profiles. An integrated unified user model and a method for its development and data gathering are proposed. The integrated and unified user model is provided for the usage in the proposed adaptation architecture. A method for the analysis of user activities in data source systems is provided that can be used as data source for the evolution of the data model of the data warehouse used in the measurement system which is described in the fifth chapter of the Thesis.

In the fifth chapter the concepts in business process measurement and performance measurement are introduced. An overview of performance measurement systems is given and a data warehouse is analyzed as a possible solution for the implementation of the performance measurement system. In this chapter a performance measurement framework is proposed that is based on the indicator life cycle. An indicator definition metamodel is defined and a method of how the indicators can be used in the performance measurement framework is given. In this chapter a method for two level measurement of business processes is given. The solutions are described using an approbation in real life projects. The method is used to support an appropriate choice of indicators and their properties within the performance measurement framework.

The results and conclusions gained during the research and the process of writing of this Thesis are given in the conclusive chapter.

2. Summary of the Thesis Content

2.1. Theoretical Basis of the Research

2.1.1. Web Information Systems

Fraternali (1999) described web information systems (WIS) as a hybrid between a hypermedia and an information system, however the concept has been introduced a year before. In 1998 Tomas Isakowitz and his co-authors introduced a concept of web information systems to denote „information systems based on Web technology" (Isakowitz et al., 1998).

Panhilla (2006) described WIS as systems, that are developed with web technologies, that work with a browser, that are concentrated on the execution of the tasks, and are focused on continuous user interaction with the system.

Web information systems use web technologies to implement the needs of professional information systems (Frasincar et al., 2002). When WIS are used in business context, this implies the necessity to apply directly or adapt the principles, that are used in the development of traditional information systems, that are based on database technologies.

Houben (2004) stated, that WIS differs from the traditional static web pages or „surface web", that contains manually created content. One significant different feature of WIS is so called „ deep Web" with a content that is stored in a database. WIS requires working with data, that is dynamic, is considered in schema level and is processed in large volumes.

WIS differ not only from the „surface web", but also from the traditional information systems, because they have the potential of reaching a much wider audience using various platforms (Isakowitz et al., 1998). There exist growing needs to integrate data from different heterogeneous data sources, which are widespread in the Web. With a wider potential audience comes also a necessity to adapt these systems to the needs of different users.

2.1.2. Adaptive Web Information Systems

Brusilovsky (1996) defined, that „by adaptive hypermedia systems we mean all hypertext and hypermedia systems which reflect some features of the user in the user model and apply this model to adapt various visible aspects of the system to the user".

Adaptive system adapts the interaction, based on the user and his needs. However, there exists distinction between two concepts – adaptive and adaptable systems (Brusilovsky, Maybury, 2002), (Koch, 2000). The definitions of these concepts are following:

For an adaptable system it is necessary, that a user himself specifies, how the system's functioning should differ. The user can configure some parameters of the system and the system accordingly changes its interaction. The user or an external system makes a decision when and how the user model should be changed. Configuring in this case means the changes of values for user preferences.

Adaptive systems automatically adapt itself to the user, if the user model is given. The system monitors the user activities, registers these actions and dynamically adapts the system according to the actual user model. To construct the user model, the system takes into account browsing activities of the user and user's direct answers to the questions, for example, collected in the form of initial information, that user provides in the beginning of the work with the system.

The adaptive hypermedia and web information systems are based on collection of connected information entities, that allows to the user to navigate from one information entity to another and to find necessary information. The adaptation in this case is limited with three adaptation types: content adaptation, navigation adaptation and adaptive presentation (Brusilovsky, Maybury, 2002). Adaptive hypermedia systems often serve as a basis to develop architecture of web information system.

In the context of WIS it should be mentioned the WIS engineering (WISE). Adaptation and personalization is an aspect of the systems development, that has gained wide attention, however in different WISE methodologies the adaptation has still not been supported enough (Houben, 2004). Practically the adaptation aspects are hard to specify; it is difficult to combine them also with other WIS development aspects, for example, performance. Some methodologies allow to define rules, how the information should be delivered to the user.

Context, profile and configuration are essential concepts for adaptive WIS to describe, how the adaptation is implemented.

Context describes a set of attributes that characterizes the capabilities of the access mechanism, the preferences of the user and other aspects of the context into which a web page is to be delivered.

Profile is used to represent different context dimensions on different levels of details (De Virgilio, Torlone, 2005) and to describe the user's data requirements (Abbar et al., 2008).

Configuration defines how the information should be delivered to the user taking into account the query of the user, his context, and corresponding to the adaptation requirements that are described in his profile (De Virgilio, Torlone, 2005).

There are proposed many architectures and methods for WIS adaptation (De Virgilio, Torlone, 2005), (Valeriano et al., 2006), (Abbar et al., 2008), (De Bra et al., 1999), (Tvarožek et al., 2007). However, when new approaches for WIS development appear, a need for new solutions for WIS adaptation becomes obvious.

2.1.3. The Concept of Multi-Tenant Web Information System

When providing to the user an appropriate WIS, it should be considered also development approaches for flexible and cost effective systems, for example, Software Product Line approach (Clements, Northrop, 2002) or Software as a Service (SaaS) approach (MS06).

Software as a Service (MS06) is defined as a „software deployed as a hosted service and accessed over the Internet". The organizations subscribe to use the SaaS software and pay for the usage. The service vendor hosts the SaaS application on their servers and maintains the software and infrastructure. This is often a cost efficient solution for small and medium size organizations.

SaaS applications can be provided at four different maturity levels: 1) client application; 2) configurable application; 3) configurable, multi-tenant, effective application; 4) scalable, configurable, multi-tenant, effective application. In the first two cases the user gets his instance of the WIS. In the case of multi-tenancy all users use the same WIS instance. In the last 4th level the user gets his instance of the WIS and an additional layer is introduced for balancing system's performance.

In the case of SaaS applications the focus of the research is usually the configuration. One of existing methods, which supports the adaptation of the multi-tenant WIS, uses the software architecture as a tool for coordinating the work of functional components and configuration components (Wang, Zheng, 2010). Other methods accomplish the configuration by means of external models or formal methods to describe the configurability (Wei et al., 2008), (Kwok et al., 2008).

Each tenant of the web information system, that is based on SaaS approach, has usually its own specific needs, how the business processes are organized, therefore the SaaS application should be adapted to the needs of each tenant. It is also important that the tenant must pay for the usage of the system; therefore the tenant is interested in payment only for necessary functions or modules. The configuration of functions in SaaS applications solves the problems with different requirements to allow adaptation of the system for tenants from different businesses.

The user interface should only present the necessary functions. The configuration of the user interface is implemented by configuring of the presentation elements, for example, menus and displayed content elements.

The architecture presented in the Thesis is provided for a WIS usage context, where many similar organizations use the same WIS, but each of them gets its own adapted instance of the WIS. Two level adaptation is implemented. Not only the organization, but also the user gets his adapted instance of WIS.

2.2. Research Methods Used

2.2.1. The Proposal of the Architecture for Multi-Tenant Adaptive Information Systems

Software architecture is defined as "the fundamental organization of a system embodied in its components, their relationships to each other and to the environment and the principles guiding its design and evolution" (ANSI/IEEE Std 1471-2000).

An architecture is proposed in the Thesis for Multi-Tenant Adaptive Information Systems (MTAIS), which is planned to support the usage of WIS in several organizations from the same business area with similar business processes by adapting the WIS for needs of each organization and user (Niedritis, Niedrite, 2011).

MTAIS architecture that is proposed in the Thesis is based on following principles:

- The Software as a Service (SaaS) approach is used in its 3rd level of maturity; the multi-tenant and one instance solution is used. It is assumed, that WIS or part of it will be used by organizations with similar business processes, which will be supported by the adapted WIS.
- Web information systems that store the data in the database and implement some business logic are handled. In the case of large number of users and business processes it is necessary to ensure for each user appropriate functioning of the system according to the user's context,
- SaaS approach is extended with a two level adaptation possibility, where the system is adapted at the organization level and at level of individual users; corresponding adaptation operations are defined,
- The navigation adaptation for the system is also determined by changes of data made by the user; accessibility of functions depend on the changes of the objects' status, that is modified by the user,
- The functioning of the system also depends on the context of the user's interaction with the system, for example, depending on the interaction time some functions could not be available to the user;
- The adaptation is based on the development of an user model and analysis of user actions to supplement the data of user model. The data can be changed as a result of performing business processes or when the user modifies his data in the context of business processes or when other users change data about the particular user;

- Adaptation architecture as a significant part also contains a measurement system to maintain and improve the multi-tenant WIS that is built according to the proposed adaptation architecture

The proposed MTAIS architecture has four layers:

- Context layer defines the interaction of the user with the web information system. The context in this interaction depends on the user of the system, the place and time of the interaction, the device used for the interaction, and also organization, whose instance is used by the user,
- The component layer defines the WIS that should be adapted, its structure, parts, among them also function groups and functions of the system. This layer also includes the components, that are needed for the maintenance of the adapted system, among them, for example, the performance measurement system,
- The adaptation layer consists of MTAIS architecture components that support the adaptation of the WIS,
- The data layer stores both WIS business data, and data for the needs of adaptation implementation. Performance measurement data are also stored in this layer.

The MTAIS architecture and its components are presented in the Thesis based on following principles: 1) they are described from the perspective of the adaptation implementation, 2) the place and role of the user model for the adaptation and measurement support within the architecture is described, and 3) performance measurement issues within the architecture are described, including components from the component and data layer.

Description of the MTAIS architecture and its components from the perspective of the adaptation implementation in the Thesis is based on the schema from Figure 1, which contains the components of MTAIS from all architecture layers that are necessary for adaptation and shows the components connections:

1. Context monitor identifies the context properties of the system usage in the time, when the user connects to the WIS. The context monitor compares the identified context properties with values of corresponding elements in profiles of MTAIS architecture to find out values of additional attributes in profiles that also characterize the context. Then the characteristics of the context are passed to the adaptation component of MTAIS architecture.

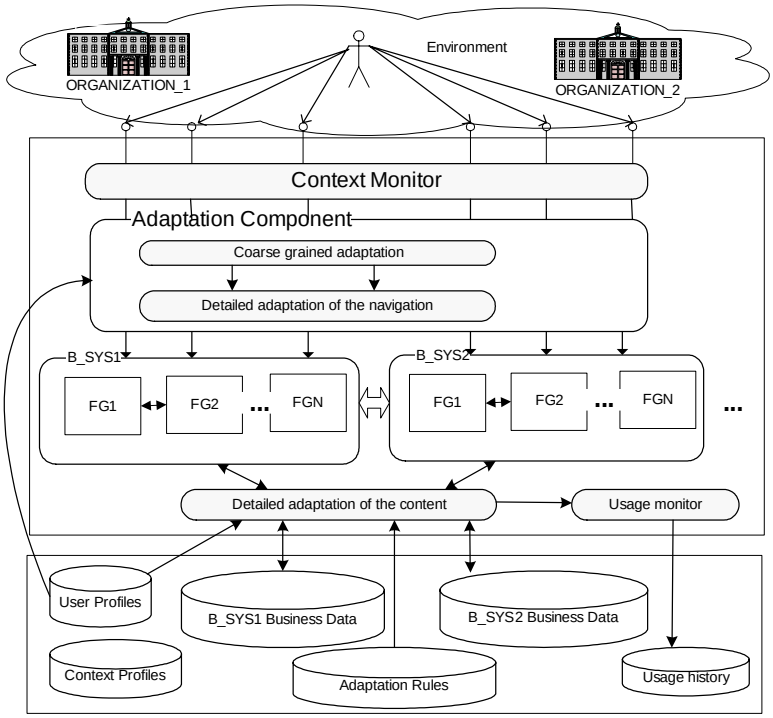

Fig. 1. Architecture for Multi-Tenant Adaptive Information Systems

2. Adaptation component starts with the identification of the initial configuration of WIS and performs its adaptation in two levels:
   - Coarse level adaptation process recognizes the groups of functions that are accessible to the system user according to the usage context. On the picture (Fig. 1) the function groups are depicted as FG1, FG2 etc. According to the defined configuration and organization profiles an adapted WIS organization level instance is created. MTAIS architecture also ensures support for the situation when one user can be connected with several organizations; as a result several adapted WIS instances for these organizations are created. In this case for the convenience of users the MTAIS architecture combines several WIS instances into one united WIS interface according to predefined transitions given in the configuration profile. The organization level instances of WIS (Fig. 1) are depicted as B_SYS1, B_SYS2 etc. The picture shows the situation, when the user is connected with two organizations, that are tenants of given WIS.
   - Detailed level adaptation is based on the information stored in the user profile. The detailed adaptation consists of two steps:
     - Detailed adaptation of the navigation uses the profile information about the functions accessible to the particular user and within the framework of the organization level instance of WIS, provides an adapted navigation between all functions allowed for the user.
     - Detailed adaptation of the content constructs an instance of WIS for the particular user according to the user profile, which describes the data accessible to the user, and according to the user functions identified in the previous step; data allowed to the user are included into the adapted WIS instance for the user.
3. Usage monitor is planned to collect data about the used functions of the adapted WIS instances. The goal of this action is to provide information for the monitoring and analysis of processes supported by the WIS and to use these data to develop a strategy for the successful further development of WIS. The collected information is also planned to use for analysis of amount and patterns of WIS usage to determine appropriate payment for the WIS usage and maintenance. The usage monitor is implemented according to the performance management framework proposed in the Thesis and according to the two level measurement method, that allows evaluation of each WIS instance as a separate information system. This method can also be used separately in one organization, if the WIS instance is evaluated in comparison with other information systems in the organization.
4. WIS data layer contains profiles that are used in both adaptation levels and business data corresponding to WIS. During the coarse grained adaptation process a virtual data store is built; the virtual data store contains the data owned by the organization. The data that is accessible to the user is determined during detailed adaptation of the WIS to create the content of the user interface. WIS data layer also stores information about usage history of WIS functions, which is collected by the usage monitor. The adaptation rules database stores implemented procedures for adaptation operations, which are used to perform adaptation operations during the creation of the organization level or user level adapted WIS instances.

2.2.2. Implementation Techniques of the MTAIS Architecture

Profiles of the data layer of MTAIS architecture

MTAIS architecture uses profiles, that define metadata, that serves as a basis for the execution of adaptation operations. Each particular profile describes some of essential aspects of WIS adaptation. Configuration profile describes the structure of adapted WIS, which functions are part of the system and how they are grouped. Organization profile describes the organization, which uses the adapted WIS for support of its business processes. Also its connection to the configuration profile is defined, including which particular WIS functions are implemented and used for this organization, and therefore are subject to adaptation. User profile describes WIS user, for example, the connection of the user with organization,

that uses WIS and user rights in WIS are described to support creation of an adapted WIS instance that corresponds to the user needs. The profiles of the MTAIS architecture are defined using UML class diagrams.

Presentation model of MTAIS architecture

To describe how the WIS instance is presented to the user at the organization level, MTAIS architecture uses a presentation model, which elements describe the structure of the WIS user interface. The MTAIS architecture supports the presentation adaptation only in such extent to ensure the presentation of functions and data available to the user, therefore this assumption determines the elements of the presentation profile.

Adaptation operations

The result of the adaptation is a WIS instance adapted in two levels:

1) The result of coarse grained adaptation is an organization level WIS configuration that corresponds to the needs of the particular organization. The adaptation result is also joining of function groups from different WIS instances, if a user belongs to more than one organization using the WIS, and this situation is defined in the profile.

The coarse grained adaptation is performed by the following operations according to the context:

- The construction of initial configuration of WIS
- The WIS adaptation in organization level
- The joining of instances of function groups
- The selection of allowed function groups
- The adaptation of layout

2)The result of detailed adaptation is a WIS instance adapted for the individual needs of the user, which is characterized by adapted navigation and adapted content. The detailed adaptation is based on the information from the user profile of the MTAIS architecture. The detailed adaptation has two operations:

- detailed adaptation of the navigation,
- detailed adaptation of the content.

In the Thesis the execution sequence of adaptation operations is described, how the adaptation operations are performed during the adaptation process. The usage of profiles in operations, the determination of the context in the moment of the interaction between the user and the system, and the result of the adaptation – the changes in WIS instances are also described. In the Thesis are given the algorithms for the adaptation operations.

2.2.3. Implementation of the User Interface in the MTAIS Architecture

The construction of user interface is based on the presentation model and uses profiles from the MTAIS architecture. There can be slightly different structure of user interface in each WIS development Project. The structure of the user interface depends on business requirements for each WIS and on the presentation model of MTAIS architecture. Two different structures are described in the Thesis; each of them is used in different WIS Project. They are used to illustrate two different adaptation solutions.

The Figure 2 shows the structure of an user interface for WIS that is used in WIS for universities, which is used to illustrate the creation of integrated user interface that unites data from two or more WIS instances. The Figure 3 shows the structure of an user interface for WIS, which is used in the second WIS approbation project in Vehicle register to illustrate dynamic generation of web interface according to the user actions.

Integration of user data in the user data area.

Let us consider a case, when a user has access to WIS of two organizations, which are the instances of the same WIS adapted at the organization level. However, the user for his working needs gets only one adapted and integrated user interface. An example of such united interface, whose content is created

applying both adaptation levels, is given on Figure 2. The content in this case is the functions and data accessible to the user.

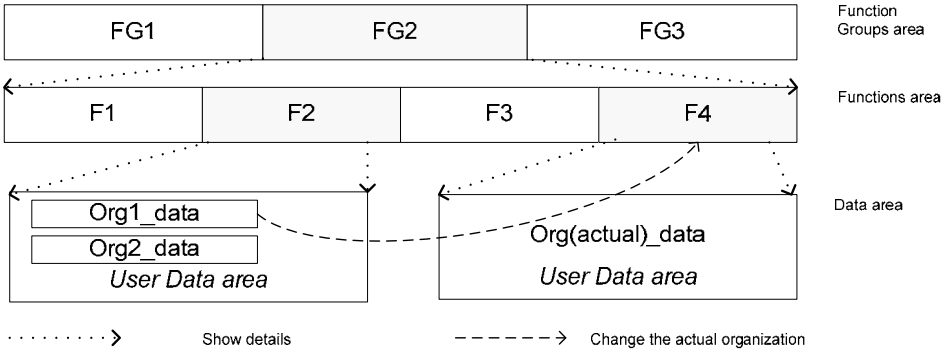

Fig. 2. Integrated user interface of the WIS in an approbation project

The elements of the interface are determined during the WIS adaptation process, and the most important actions are following:

- Determination of function groups to be presented in the interface,
- Presentation of function groups in the integrated interface according to the WIS usage time,
- Availability of special accentuation of function groups in the user interface,
- Determination of functions to be presented in the interface,
- Presentation of determinant and dependent functions,
- Integration of user data within the user data area.

Within the architecture framework we can speak about two types of data to integrate and show in an united and corresponding data area in the user interface (Niedritis, 2011). One of the data types is user data that characterizes the user as a person (identity, address, education). These data can be entered, for example, by authorized users in one or another organization or by the user himself, but these data usually are not directly connected with business functions of the organization. The second type of the data is created by the user or by other users during execution of functions that support business processes of the organization. The data integration problems arise with the first data type. The cause of this is the data ownership, when the user is client of more than one organization that uses the WIS. Following solutions are used to store, modify, and maintain actual, reconciled, and integrated user data: 1) on business logic dependent statuses are used to determine the ownership of each value for the data item, when data items are common for all organizations, 2) a predefined set of attributes is stored for each organization in separate records. In the user interface all data items that correspond to the user's profiles in all organizations can be displayed.

Adaptation of the user interface according to the user actions

The interface can be generated with a close involvement of the user into the process. The choices of the user and the later interface construction depend on statuses of an object that is a focus of activities during business process completion. The user of a web-based business information system gets an interface of WIS that is suited for the specific business situation. (Niedritis, Niedrite, 2012). This is part of the organization and user level adaptation.

User actions influence the WIS adaptation in the following ways:

- *Choice of the object.* The user finds the object that will be the focus of activities during the later business process completion.
- *Creation of a state dependent function list.* The initial state of the object determines the available operations that can be applied to the object. The list of operations (functions) depends on the configuration profile of the MTAIS architecture. The list of functions is presented in the user interface as presentation elements of navigation type. Let us see an example (see Fig. 3), which

describes a situation with chosen object O1 with an initial state S1 and a list of allowed three functions F1, F2, and F3 with defined initial and final states. The user can then select either a function F1 or F3.

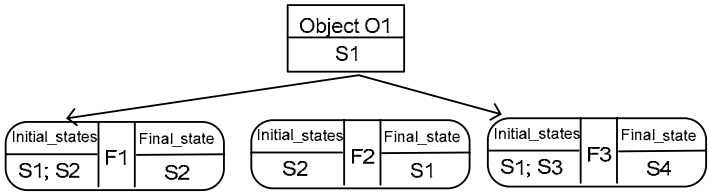

Fig. 3. An example of states of the object and functions

- *Choice of the function and change of the object status***.** According to the business needs, the user selects sequentially all necessary operations that should be performed with the object from the list of allowed operations displayed to him.

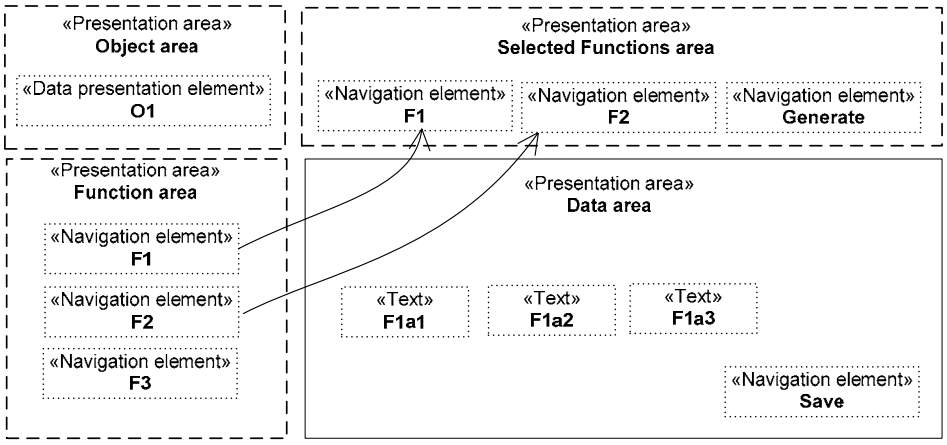

Fig. 4. User interface for given example

- *Generation of the presentation for the given function group.* The user finishes the selection of functions and generates the presentation area that contains data presentation elements. In the given example from the Figure 3 the presentation for WIS instance is given in Figure 4, which shows the user choices and delivery of allowed and state-dependent functions to the user.
- *Performing tasks with data elements.* This step does not influence the user interface and can only influence the values of object's attributes. Also, the attribute (or attributes) that defines the state of the object can be changed. The object status changes can cause modifications in the interface, if new functions became available, that should be represented in the interface.
- *Performing validity check for mandatory presentation elements***.**
- *Saving the data.* If the validity check is successful, the user can save changed data elements and start constructing a new workflow by selecting a new object.

2.2.4. User Model in the MTAIS Architecture

It is characteristic for adaptive systems to have an explicitly defined user model, which represents user's knowledge, goals, interests and other features, that allow to the system to distinguish different users.

Adaptive system collects data for the user model from different sources, that can include both indirect observation of the user, when the user interacts with the system, and direct request to enter the data about the user (Brusilovsky, Maybury, 2002).

User model is an abstract representation of the user; only certain and essential features of the system are included into the user model. Systems view about the user is created. User profiles are simple user models (Koch, 2000).

External systems and organizations internal systems store the information about different features of the same user, the goal of the information gathering can be different – identification, control, adaptation (Brusilovsky, 2001), personalization (Koutrika, Ioannidis, 2004), recommendations and other goals. The user profile of each system describe the user from different aspects, for example, interaction, geographical, demographic and other aspects that are essential in the context of given systems. There are also ontologies that describe the user (Razmerita et al., 2003), (Zhang et al., 2007).

The information entities about the users stored by the systems can be used to get a comprehensive view about the user. Integrated information about the user can serve as a new information source about the user. The life-cycle of the user profile consists of three stages (Gauch et al., 2007): (i) information gathering about the user, (ii) creation of an integrated view about the user (development of a integrated profile) and (iii) usage, that provides a personalized service to the user, based on the user profile

The recent research in user model development is connected with the user model integration. For example, in social web (Abel et al., 2010) an existing user profile can be used, when a user becomes a WIS user. Berkovsky et al. (2008) and (2009) proposed a mediation platform, to extend the user model with import and integration possibilities. Niederee et al. (2004) suggested usage of the same user model in different systems, but with extensions and improvements.

The development of integrated user model in MTAIS architecture

The integrated user model and its development method described in the Thesis is developed in the research project about data warehousing and is based on some results of other project participants, for example, in previous works a concept of user-describing profiles for data warehouses was introduced (Kozmina, Niedrite, 2010). These user-describing profiles are provided for personalization purposes of data warehouses and describe the user from the Place, Time, User, Recommendation, Preferences and Interaction aspects.

Based on the user-describing profiles, an integrated user model is developed in the Thesis (Niedritis et al., 2011b).The user-describing profiles are extended to get a general user model that represents the needs of more than one system that have their own user profiles. The data about users are gathered within each particular system, and then the integrated user model can be used in these systems and in a data warehouse for different purposes. Following principles are used:

- User-describing-profiles were merged with some structures of the learner profile (IMS), because the research results and also Thesis results were approbated in the university, therefore a standard used in education sphere that describe system users was chosen. In other cases corresponding standards for the particular sphere that describe its system users should be used.
- The user model is generalized for the case of several systems, because the method is provided to integrate the data from user profiles of many systems,
- The user model needs to ensure the extensibility by allowing to add to the model new, system-specific attributes, when a new system is introduced, and in the integrated user model the data from the new profile should also be added.

Gathering of data for the integrated user model in the MTAIS architecture

Because the user model is developed in the MTAIS architecture, whose one component is the performance measurement system that is based on data warehousing technologies, then also for the development of the integrated user model following data warehousing techniques and methods are used: mapping definition, data integration and data storing in the data warehouse database.

Schema on the Figure 5 defines components and data exchange directions of the system and data Exchange directions of the user models among components. The main steps of the user profile integration process are following: component for mapping definition defines mapping from each particular user model to the integrated user model; the user model extension component allows adding new attributes to

the integrated user models, if some attributes from particular user model are not presented before in the integrated user model. Then gathering of user data is performed, using data warehouse data gathering procedures.

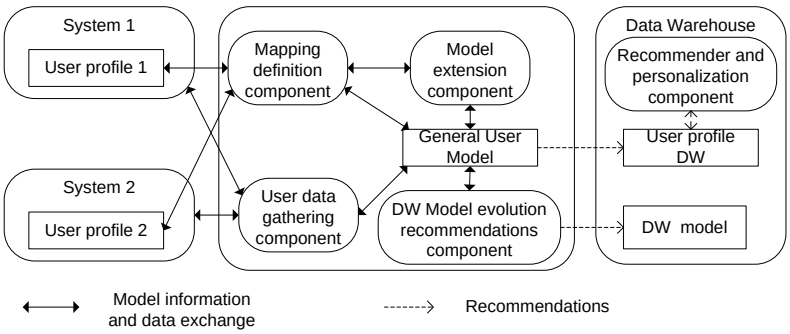

Fig. 5. Data gathering and usage of the integrated user model

The usage of the integrated user model in MTAIS architecture

The user model is used for following goals:

- User profile that is a subset of the integrated user model is used in the MTAIS architecture for adaptation purposes of WIS,
- The recommendation component prepares recommendations for defining the user rights in the data warehouse,
- Recommendations are prepared to recommend also further development of the data warehouse model, for example, which new data cubes may be useful for the users, based on the collected information about user activities in the source system,
- In the Thesis a method is provided for application of the user model in the performance measurement system to determine evolution options of the data warehouse,

The method for evolution of the data warehouse model for the performance measurement system

The integrated user model can also be used in the performance measurement system, which is based on a data warehouse. In the Thesis a query-driven method is proposed (Solodovnikova et al., 2012), that determines the information needs of users from the existing queries of users and their usage statistics. The method assumes that the queries against the source system's database reflect the analysis needs of users. The method recommends the changes in existing data warehouse schema and uses version support of the data warehouse, to keep track on all changes of the model.

There exist different development methods of conceptual models for data warehouses. Demand driven methods are classified according to the way how requirements are elicited, for example, there are user-driven (Westerman, 2001), process-driven (Kaldeich, Oliveira, 2004), or goal-driven (Giorgini et al., 2005) methods. Often the quicker and more simple method type is used that can be classified as data-driven methods (Golfarelli et al., 1998), because they transform the models of data source systems into the models of data warehouses. However, new methods are still proposed for overcoming shortcomings of existing methods. Following shortcomings should be mentioned: data driven methods automatically develop a model that at the end of the process may not reflect actual needs of users, but for the requirement-driven methods the result (model) depends on knowledge of interviewed users, moreover, the existing data that are available in data sources are not taken into account.

The proposed method uses the existence of different log files in the system, that collect information about activities and data modifications. The proposed method for schema evolution of a data warehouse allows following the real usage of data in the source systems of the data warehouse and adjusting the data warehouse schema to the most often used data items in user queries and data manipulation statements.

2.2.5. Development of the Performance Measurement Framework in MTAIS Architecture

Process measurement system is included into the MTAIS architecture, because, when a complicated system is maintained, that has many adapted instances for needs of different organizations and employees of these organizations, it is necessary to measure and analyze different aspects:

- Usage characteristics of the system in the organization: what exactly is used, to describe quantitatively the functions usage at the organization level, for example, usage frequency and number of users,
- Analysis of usage patterns of the users by performing a detailed analysis, which data are used to perform the business functions.

Measurement goals in the organization can be different. Usually the results of business processes are measured; the performance indicators are defined before the measurement to follow the progress of the business or to find out necessary reengineering of business processes. In the MTAIS architecture following measurement goals are defined:

- Estimation of payment for the WIS usage,
- Determination of priorities for the WIS development,
- Optimization of WIS technical parameters,
- Personalization and recommendation needs.

Process measurement system that is based on data warehousing technologies can be created, if a data warehouse already exists in the organization, that is used to analyze organization results, for example, to analyze financial indicators, but the necessity to analyze process aspects became obvious later.

Measurement according to Fenton and Whitty (1995) is "the process by which numbers or symbols are assigned to attributes of entities in the real world in such a way as to characterize the attributes by clearly defined rules." There exist ontologies, methods (Munson, 2003), (Garcia et al., 2006) for determination of indicators in some industries, e.g. Software process measurement. In the business process measurement, the measurement is considered in context of its applications, e.g. business process reengineering or performance measurement.

The indicators can be defined on various levels of formality. Some proposals on how to specify formally performance indicators exist and are described: (Frank et al., 2008) provides a formal language for goal modeling, but (Popova, Treur, 2007) proposes formal language for indicator definition by introducing the sorts of indicators, predicates and functions included in it.

Measurement systems have to be developed according to the strategies of the company and according to one of the management models, for example, Balanced Scorecard (Kaplan, Norton, 1996). Data warehouse could also be used for implementation of performance measurement system (List, Machaczek, 2004), (Jarke et al., 2000), (Kueng et al., 2001).

Effective organization of business processes ensures the achievement of the institution's goals. During the performance measurement the measurement results should be compared with the target values to make decisions, whether goals are achieved or not. Organizations use performance measures to align daily activities to strategic objectives (Parmenter, 2010).

Performance measures (Parmenter, 2010) refer to indicators used by management to measure, report and improve performance in an organization. Performance measures are classified as key result indicators, result indicators, performance indicators, or key performance indicators (Parmenter, 2010). Therefore an important question arises how to chose appropriate measures, how to formally describe them and how to define a corresponding measurement framework.

<u>The model of performance indicators and the five step life-cycle of indicators</u>

Previously described concepts about the performance measurement and indicator properties are taken into account to discover and describe the nature of indicators in the most comprehensive way. In the Thesis a lifecycle of indicators is provided (Niedritis et al., 2011a), which consists of five steps – indicator definition, measurement, analysis, reaction and improvement:

- **1. step.** Indicator definition step describes different features of the indicators, that help to understand, why each indicator is introduced,
- **2. step.** Measurement step represents the process when the indicators get their values,
- **3. step.** The analysis step represents the process, when indicators are used to make decisions
- **4. step.** The reaction step represents the process, when the decisions are implemented,
- **5. step.** Improvement step supports the evaluation of indicator definitions and values of their aspects; recommendations of changes in these values can be provided.

In the Thesis different indicator aspects are analyzed, that are obtained during literature analysis about indicators (Parmenter, 2010), (Muehlen, 2001), for example, perspective, time, responsibility, activities, success factors, and reports. In the indicator life-cycle that is proposed in the Thesis the indicator aspects are grouped according to these five steps; additional new aspects are introduced in this model, for example, measurement level.

The performance measurement framework with indicators raise two further questions: (i) what is the most suitable implementation to support the proposed indicator life-cycle, and (ii) how the indicators can be formalized to most clearly describe what, why and how is measured.

Software requirements are normally described using a requirement specification language with various levels of formality (Videira, Silva, 2005). In the case of performance measurement in the Thesis metamodel from (Kozmina et al., 2008) is extended to express the indicators. We based the proposed model (Niedritis et al., 2011a) on structure evaluation of the sentences that formulate performance indicators taken from the appendix of Parmenter's book (Parmenter, 2010). In the Thesis the principles are given to reformulate business requirements defined in natural language according to unified pattern. All indicators have similar structure, therefore it is possible to define pattern how to document the indicators formally. This approach for the formal definition of the indicators uses model that is described with UML 2.0. class diagram.

Performance measurement framework

In the Thesis a measurement framework is proposed (Niedritis et al., 2012), that describes different measurement aspects. After implementation of the measurement framework, the quality of the measurement process is improved, because it helps to ensure that necessary indicators are analyzed in right time, according to the context, and as a result appropriate actions are performed. Usage of an existing data warehouse gives additional advantages in performance measurement. The analysis of indicator values can be performed by means of an existing OLAP tool (Solodovnikova, 2007), reports of the data warehouse or graphical tools.

In the Thesis a framework is proposed for creation of performance measurement systems by substantially exploiting existing data warehouse technologies. It is grounded on the following principles of design and operation:

- Processing of indicator information is performed in conformance with the life-cycle of indicators and formal indicator model,
- Measurement data are obtained through an ETL process and stored in a data warehouse;
- Indicator analysis aspect is provided by using a ready-made data warehouse reporting tool extensively both for obtaining actual value from measurement data and providing users with detailed reports.

The kernel of the performance measurement framework (Figure 6) consists of performance management component and the indicator life-cycle support database, as well as the dashboard module.

Performance management component is the main part of the framework that is intended for monitoring of business processes by analyzing the measurement results of indicators. Component is based on descriptions of different properties of indicators that are stored in the Indicator life-cycle support database and that allow the user to analyze the indicator values by means of two other components of the framework – Dashboard module and the Reporting tool. The Dashboard module visualizes the most

important indicators comparing them to the stored target values of indicators. The reporting tool provides more detailed information to the user by calling predefined reports. An existing reporting tool is used; more information about this tool can be found in (Solodovnikova, Niedrite, 2011).

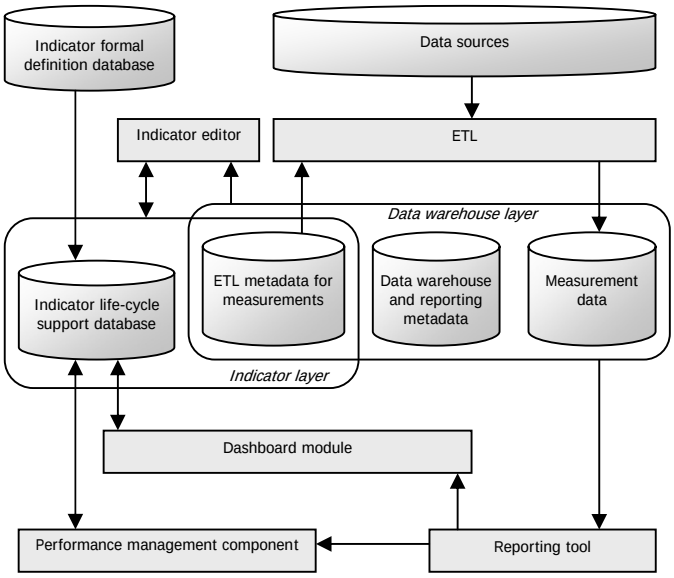

Fig. 6. Components of the performance measurement system

The performance measurement is done according to the schema on the Figure 7; in the Thesis according algorithms are also given to perform all steps of the measurement process.

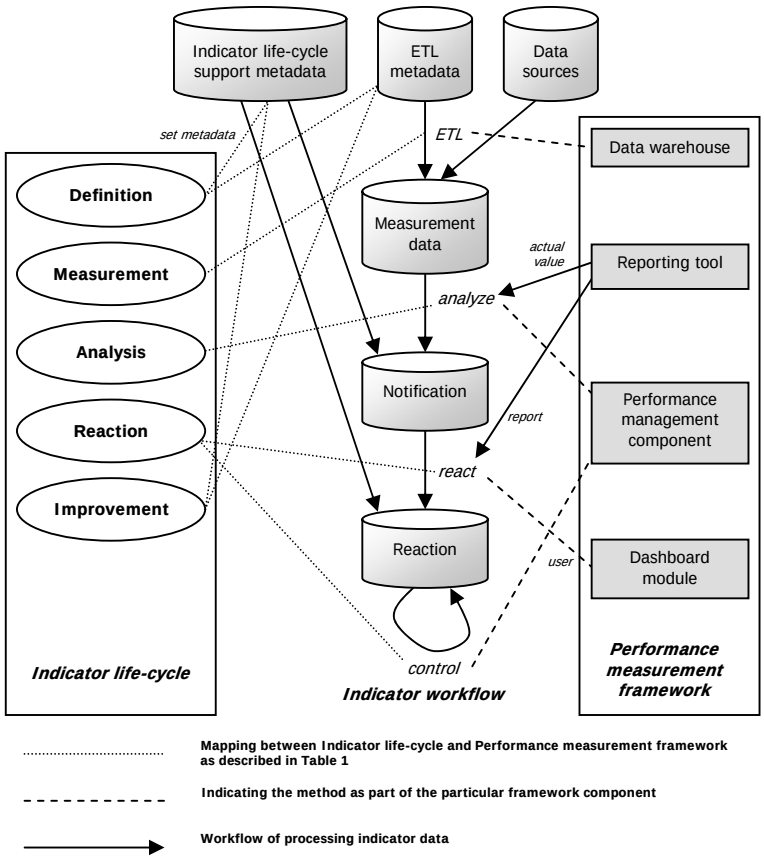

Fig. 7. Indicator life-cycle support implemented by the Performance measurement framework

- Measurement step is performed by an data gathering (ETL) process of the data warehouse
- In analysis step measurement data are processed according to indicator life-cycle support metadata by the Performance management component. Reporting tool is used here to obtain the actual value of the corresponding indicator. During this step, a record is added to the indicator life-cycle execution data; thus, the information about the performed measurements of indicators in form of a notification becomes visible to appropriate users in a special dashboard,
- User's reaction is obtained from the Dashboard module and can be of two types: 1) a request for the detailed notification; reporting tool is used here to obtain a report that describes the actual measurement in detail; 2) reaction, if the description of an indicator requests for a response.
- In control step Performance management component checks whether users have responded to the notifications in time and in appropriate way, if such reactions were appointed in the analysis step.

Two level approach for measurement of business processes

A lot of research is devoted to discovering of what is the most appropriate way, how to measure the effectiveness of the information systems. Different particular measurements are considered in these research projects, for example, system usage (Cuellar et al., 2006). However, there are not many models that represent several information systems effectiveness measures and connections between them. In the „"IS success" (effectiveness) model (DeLone, McLean, 2002) stated that to prevent misunderstandings with the system usage measurement it is also necessary to additionally characterize the usage level of the system, the nature of the usage, and suitability of the usage.

The proposed method in the Thesis (Medvedis et al., 2008), (Medvedis et al., 2008b) considers, how to measure the usage of the information system, which is used to support business processes.

High level measurement has following essential tasks:

- Exploration of information systems of the organization, finding out the integration interfaces, documenting, to clarify the potential alternative ways of function execution, that can help to analyze and explain the measurement results,
- Documentation of the features that influence the system usage:whether the usage is optional or mandatory, for example, whether the functions are done to fulfill the job responsibilities or not; the access control type, and existence of user access mechanism, that restricts wide usage of the system,
- Development of the process measurement system, that is designed according to chosen measurement indicators, and anticipating that this system will also be used a for the detailed measurement,
- Definition of the measurement goals in each level. In the high level measurement such goal could be, for example, discovering the system, whose usage indicators change, to be ready for a detailed analysis to find out the reasons of changes, if it is necessary. Another measurement goal could be in connection with payments, for example, finding out, if the investments are cost-effective, or as in case of SaaS architectures – the measurements can serve as an information source for estimating the payments from the organization about usage of the information system.
- The choice, definition, and description of indicators according to the measurement goals, in the high level measurement they are connected with the information systems usage.

Detailed measurement level includes detailed measurement of particular business processes. At this measurement level the functions of the information system, that support a selected business process, are examined and measured. Measurement goals in this case usually are connected with reengineering of business processes; indicators that are connected with a process are measured.

The process measurement system uses as a part a data warehouse, which in the context of MTAIS architecture is included in the performance measurement system.

The process measurement and monitoring system (PMMS) was created as an integrated part of management information system LUIS (Niedrite et al., 2007a).

One PPMS essential component is the data warehouse; other components are: 1) process operational monitoring component, 2) process measurement system, and 3) process execution log.

2.3. Main Results of the Thesis

The MTAIS (Multi-Tenant Adaptive Information Systems) architecture is developed, that is based on the multi-tenant single instance SaaS application approach, but in the Thesis proposed MTAIS architecture new features are provided:

- Two level adaptation option – for organization level and for individual user level,
- Adaptation is based on the comprehensive user model that is developed in the Thesis, that includes different user describing aspects,
- Dynamic generation of the user interface of the adapted web information system according to the user model is supported,
- The architecture also includes the performance measurement component, that is provided for development, maintenance, and usage evaluation of the WIS that is developed according to the principles of MTAIS architecture,
- The measurement component is based on the measurement framework that is proposed in the Thesis, and that is based on the five steps indicator life-cycle, which allow to use the indicators for the process measurement in a consistent way,
- For the measurement support a two level measurement approach is provided: system level measurement and process level measurement.

2.4. Limitations of the Research

The MTAIS architecture that is provided as the research result has some restrictions:

- The proposed architecture is targeted to the adaptation of WIS functionality and of data access within the MTAIS architecture framework according to the usage context, however, the WIS presentation adaptation is considered in a reduced manner. The adaptation for the mobile devices is not considered, adaptation of different visual layouts is restricted to some features only (logo, background color).
- The presentation adaptation possibilities are results of navigation and content adaptation, and are implemented according to the presentation model of MTAIS architecture to provide to the user the allowed to him functions and data. The presentation model of MTAIS architecture is targeted to present the adaptation result as functions and accessible data and do not include elements to describe detailed visual design.
- In the Thesis proposed MTAIS architecture can be used for a type of web information systems, where it is necessary to achieve creation of a high number of different adapted WIS instances and the layout aspects are not so essential.

3. Main Conclusions of the Thesis and Proposals

The hypothesis that was formulated in the Thesis that says “it is possible to perform effective development of web information systems based on innovative architecture which carries out the software as a service approach” has been confirmed. This is demonstrated by the results of the Thesis and approbation of the results in two projects.

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For the information system, that is based on the proposed architecture, the development effectiveness can be evaluated using following criteria:

- Within one organization the developed information system ensures adapted functionality according to the organization's business processes, which is continuously improved. The fulfillment of this criterion is confirmed by application of the two level measurement approach, where the analysis of the system usage and process execution is performed.
- The web information system is developed foreseeing the possibility to maintain and simultaneously use adapted instances of the system in many organizations. The fulfillment of this criterion is confirmed by usage of the proposed architecture in two approbation projects, where two web information systems were developed and later used in many organizations. One of them is used in a project, where 13 universities use 13 adapted instances of WIS, and in the other project, where the vehicle register WIS is used by Road Traffic Safety Directorate and by other external organizations.

Practice shows that this architecture can be used in various business areas. Applying this kind of architecture can be considered in the following situations: 1) there are users who use more than one instance of WIS simultaneously or consecutively accessing all their data; 2) many users carry out the same function, but each of them in a different way.

The MTAIS architecture that is proposed in the Thesis is characterized by the following innovative features:

- Two-level adaptation is proposed for WIS adaptation – organization-level and detail-level – for the users. As a result of organization level adaptation, an adapted WIS instance is created based on organization profile that describes WIS functions and how they are used in the organization. Adaptation on user level is based on the user profile, and WIS is adapted according to the specificity of individual user's work with the system.
- In the framework of the architecture both components that are necessary to ensure the adaptation and the interaction possibilities among the components are defined. For the interaction needs of the architecture's components there are adaptation operations that are defined in both adaptation levels.
- The architecture supports the situation when users work with more than one instance of WIS, if the user is connected with many organizations that are WIS tenants. The adapted WIS instances are integrated into one system adapted for the particular user, which is delivered to the user through an integrated user interface.
- Dynamic generation of the user interface is also supported according to the user's actions with the objects in the system.
- Methods were proposed to solve data conflicts caused by many tenants of a system that is based on the SaaS one-instance approach, which was used also to build the proposed architecture. It is proposed to describe ownership of each record and validity period and to define on the business logic level the control procedures that determine who and what can perform operations with the records in an appropriate status.
- In the MTAIS architecture a user model also plays an essential role. For the creation of the user model ideas about user profile integration were used to develop a user model and to gather data about the user. A user model is used for both – WIS adaptation, and in the performance measurement system of the organization to ensure the conformity of the system to the users' data requirements.
- As parts of the MTAIS architecture, a measurement framework, formal model of indicators, and a method for business process measurement and improvement are proposed. The proposed performance measurement framework for organizations is based on usage of data warehousing technologies. The data warehousing solutions are extended with information about the measurement process. The measurement framework, which is presented in the Thesis, provides an additional method that ensures information support for the measurement and analysis and additional control options for these tasks. It should be noted, that the proposed framework is designed for the situation when the data warehouse, its development and maintenance processes, and report tools already exist in the organization.

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