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*The Guardian of the journal's mission is its Programme Committee, which participants of which will adapt to current trends and as an answer to the changing economic and social challenges in the integrating Europe and World.*

*Tadeusz Krupa*

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# A HYBRID METHOD FOR THE MODELLING AND OPTIMISATION OF CONSTRAINED SEARCH PROBLEMS

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***Abstract:*** The paper presents a concept and the outline of the implementation of a hybrid approach to modelling and solving constrained problems. Two environments of mathematical programming (in particular, integer programming) and declarative programming (in particular, constraint logic programming) were integrated. The strengths of integer programming and constraint logic programming, in which constraints are treated in a different way and different methods are implemented, were combined to use the strengths of both. The hybrid method is not worse than either of its components used independently. The proposed approach is particularly important for the decision models with an objective function and many discrete decision variables added up in multiple constraints. To validate the proposed approach, two illustrative examples are presented and solved. The first example is the authors' original model of cost optimisation in the supply chain with multimodal transportation. The second one is the two-echelon variant of the well-known capacitated vehicle routing problem.

***Keywords*****:** hybrid methods**,** constrained search problems**,** discrete optimisation, decision support, logistics.

## 1 Introduction

The vast majority of models [1-4] of decision support and/or optimisation in manufacturing, distribution, supply chain management and so on have been formulated as the mixed integer linear programming (MILP) or integer programming (IP) problems, and solved using the operations research (OR) methods. Their structures are similar and proceed from the principles and requirements of mathematical programming. The constraint-based environments have an advantage over traditional methods of mathematical modelling in that they work with a much broader variety of interrelated constraints (resource, time, technological and financial) and allow producing "natural" solutions for highly combinatorial problems.

## A Constraint-based environments

We strongly believe that the constraint-based environment [5-7, 27] offers a very good framework for representing the knowledge and information needed for the decision support. The central issue for a constraint-based environment is a constraint satisfaction problem (CSP). CSPs are mathematical problems defined as a set of elements whose state must satisfy a number of constraints. CSPs represent the entities in a problem as a homogeneous collection of finite constraints over variables, which are solved using constraint satisfaction methods. CSPs are the subject of intense study in both artificial intelligence and OR, since the regularity in their formulation provides a common basis for analysing and solving the problems of many unrelated families [5]. Formally, a CSP is defined as a triple $(X,D,C)$, where $X$ is a set of variables, $D$ is a domain of values and $C$ is a set of constraints. Every constraint is in turn a pair $(t,R)$ (usually represented as a matrix), where $t$ is an n-tuple of variables and $R$ is an $n$-ary relation on $D$. An evaluation of the variables is a function from the set of variables to the domain of values, $v:X \rightarrow D$. An evaluation $v$ satisfies constraint $((x_1,\ldots,x_n),R)$ if $(v(x_1),..v(x_n)) \in R$. A solution is an evaluation that satisfies all constraints.

CSPs on finite domains are typically solved using a form of search. The most widely used techniques include variants of backtracking, constraint propagation and local search. Constraint propagation embeds any reasoning that consists in explicitly forbidding values or combinations of values for some variables of a problem because a given subset of its constraints cannot be satisfied otherwise [26].

CSPs are frequently used in constraint programming (CP). CP is the use of constraints as a programming language to encode and solve problems.

Constraint logic programming (CLP) is a form of CP, in which logic programming is extended to include concepts from constraint satisfaction. A constraint logic

program is a logic program that contains constraints in the body of clauses. Constraints can also be present in the goal. These environments are declarative.

The declarative approach and the use of logic programming provide incomparably greater possibilities for decision problems modelling than the pervasive approach based on mathematical programming.

## 2 Motivation and state of the art

Based on [1-4], and our previous work [6, 8-12], we observed some advantages and disadvantages of these environments.

An integrated approach of CP and mixed integer programming (MIP) can help to solve optimisation problems that are intractable with either of the two methods alone [13-16]. Although OR and CP have different roots, the links between the two environments have grown stronger in recent years.

Both MIP/MILP/IP and finite domain CP/CLP involve variables and constraints. However, the types of the variables and constraints that are used, and the way the constraints are solved, are different in the two approaches [16].

MILP relies completely on linear equations and inequalities in integer variables, i.e., there are only two types of constraints: linear arithmetic (linear equations or inequalities) and integrity (stating that the variables have to take their values in the integer numbers). In finite domain CP/CLP, the constraint language is richer. In addition to linear equations and inequalities, there are various other constraints: disequalities, nonlinear and symbolic (*alldifferent, disjunctive, cumulative,* etc).

In both MILP/MIP and CP/CLP, there is a group of constraints that can be solved with ease and a group of constraints that are difficult to solve. The easily solved constraints in MILP/MIP are linear equations and inequalities over rational numbers.

Integrity constraints are difficult to solve using mathematical programming methods and often the real problems of MIP/MILP make them NP hard problems.

In CP/CLP, domain constraints with integers and equations between two variables are easy to solve. The system of such constraints can be solved over integer variables in polynomial time. The inequalities between two variables, general linear constraints (more than two variables) and symbolic constraints are difficult to solve, which makes real problems in CP/CLP NP-hard. This type of constraints reduces the strength of constraint propagation. As a result, CP/CLP is incapable of finding even the first feasible solution.

Both approaches use various layers of the problem (methods, the structure of the problem, data) in different ways. The approach based on OR focuses mainly on the methods of optimisation and, to a lesser degree, on the structure of the problem (Fig. 1). However, the data are completely outside the model. The same model without any changes can be solved for multiple instances of data. In the approach based on CP, due to its declarative nature, the methods are already built-in. The data and structure of the problem are used for its modelling (Fig. 1).

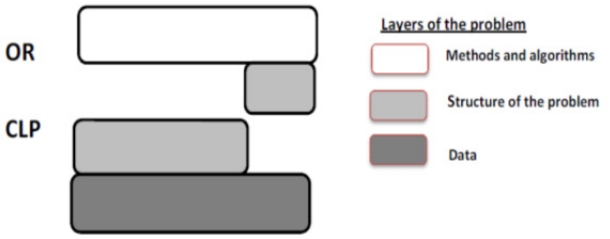


Figure 1. Layers used in the solution of the problem (OR and CP/CLP)

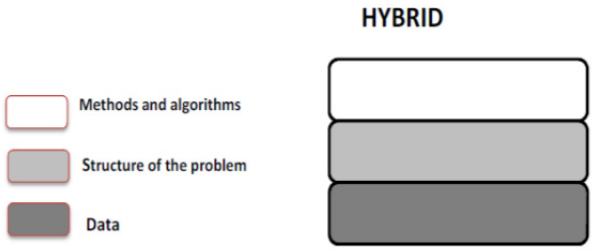


Figure 2. Layers used in the solution of the problem (HYBRID)

The motivation and contribution behind this work was to create a hybrid method for constrained decision problems modelling and optimisation instead of using mathematical programming or CP separately.

It follows from the above that what is difficult to solve in one environment can be easy to solve in the other.

Moreover, such a hybrid approach allows the use of all layers of the problem to solve it (Fig. 2).

The hybrid method is not inferior to its component elements applied separately. This is due to the fact that the number of decision variables and the search area are reduced. The extent of the reduction directly affects the effectiveness of the method.

As mentioned in Section 1, the vast majority of decision-making models for constrained problems in production, logistics and supply chain are formulated in the form of mathematical programming (MIP, MILP, IP).

Due to the structure of these models (summing of discrete decision variables in the constraints and the objective function) and a large number of discrete decision variables (integer and binary), they can only be applied to small problems. Another disadvantage is that only linear constraints can be used. In practice, the issues related to the production, distribution and supply chain constraints are often logical, non-linear and so on. For these reasons, the problem was formulated in a new way.

In our approach to modelling and optimisation of these problems we proposed the solution environment, where:

- knowledge related to the supply chain can be expressed as linear and logical constraints (implementing all types of constraints of the previous MILP/MIP/IP models [8-11] and introducing new types of constraints (logical, non-linear, symbolic, etc.),
- the decision models solved using the proposed framework can be formulated as a pure model of MILP/MIP/IP or of CP/CLP, or it can also be a hybrid model,
- the problem is modelled in CP/CLP, which is far more flexible than MIP/MILP/IP,
- the novel method of constraint propagation is introduced (obtained by transforming the decision model to explore its structure),
- constrained domains of decision variables, new constraints and values for some variables are transferred from CP/CLP into MILP/MIP/IP,
- the efficiency of finding solutions to larger size problems is increased.

As a result, we obtained a more effective solution environment for a certain class of decision and optimisation problems.

## 3 Hybrid solution environment

Both environments have advantages and disadvantages. Environments based on the constraints such as CLPs are declarative and ensure a very simple modelling of decision problems, even those with poor structures if any. The problem is described by a set of logical predicates. The constraints can be of different types (linear, non-linear, logical, binary, etc.). The CLP does not require any search algorithms. This feature is characteristic of all declarative backgrounds in which modelling of the problem is also a solution, just as it is in Prolog, SQL and so on. The CLP seems perfect for modelling any decision problem.

Numerous OR models of decision-making have been developed and tested, particularly in the area of decision optimisation. Constantly improved methods and mathematical programming algorithms, such as the simplex algorithm, branch and bound, and branch-and-cost [20] have become classics now.

The proposed method's strength lies in high efficiency of optimisation algorithms and a substantial number of tested models.

Traditional methods when used alone to solve complex problems provide unsatisfactory results. This is related directly to different treatment of variables and constraints in those approaches [2]. The proposed hybrid approach, a composition of methods as described in Section 3, offers the optimal system for specific contexts.

### A Architecture and implementation of Hybrid Solution Environment

The hybrid solution environment (HSE) consists of IP/CLP/hybrid models and a hybrid solution framework (HSF) for solving them (Fig. 3). The concept of this framework with its phases (P1 .. P5, G1 .. G3) is presented in Fig. 4.

A detailed description of the phases in the order of execution is shown in Table 1.

From a variety of tools for the implementation of the CP/CLP in HSE, ECLiPSe software [21] was selected. ECLiPSe is an open-source software system for the cost-effective development and deployment of CP applications. Environment for the implementation of MILP/MIP/IP in HSE was LINGO by LINDO Systems [22]. LINGO Optimization Modeling Software is a powerful tool for building and solving mathematical optimisation models [22].

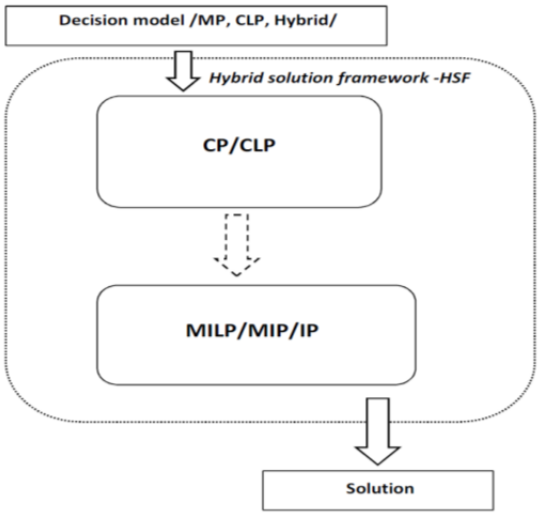


Figure 3. Scheme of the hybrid solution environment (HSE)
(*CLP - Constraint Logic Programming, CP - Constraint Programming, IP - Integer Programming, MILP - Mixed Integer Linear Programming, MIP - Mixed Integer Programming*)

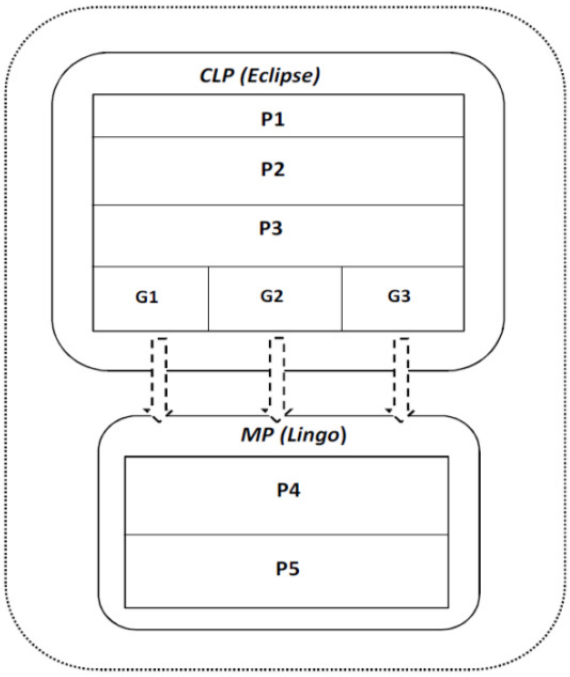


Figure 4. Detailed scheme of the hybrid solution framework (HSF)
(*CLP - Constraint Logic Programming*)

ECLiPSe software is the environmental leader in HSE. ECLiPSe was used to implement the following phases of the framework: P1, P2, P3, G1, G2 and G3 (Fig. 4, Table 1). The transformed files of the model were transferred from ECLiPSe to LINGO where they were merged (P4). Then the complete model was solved using LINGO efficient solvers (P5). Constraint propagation (phase P3) greatly affected the efficiency of the solution. Therefore, phase P2 was introduced.

Table 1. Description of phases

| **Phase** | **P1** |
|---|---|
| **Name** | Implementation of decision model |
| **Description** | The implementation of the model in CLP, the term representation of the problem in the form of predicates. |
| **Phase** | **P2** |
| **Name** | Transformation of implemented model for better constraint propagation (optional) |
| **Description** | The transformation of the original problem aimed at extending the scope of constraint propagation. The transformation uses the structure of the problem. The most common effect is a change in the representation of the problem by reducing the number of decision variables, and the introduction of additional constraints and variables, changing the nature of the variables and so on. |
| **Phase** | **P3** |
| **Name** | Constraint propagation |
| **Description** | Constraint propagation for the model, which is one of the basic methods of CLP. As a result, the variable domains are narrowed and, in some cases, the values of variables are set, or even the solution can be found. |
| **Phase** | **G1** |
| **Name** | Generation of MILP/MIP/IP model |
| **Description** | Generation of the model for mathematical programming. Generation performed automatically using CLP predicate. The resulting model is in a format accepted by the system LINGO. |
| **Phase** | **G2** |
| **Name** | Generation of additional constraints (optional) |
| **Description** | Generation of additional constraints on the basis of the results obtained in step P3. |
| **Phase** | **G3** |
| **Name** | Generation domains of decision variables and other values |
| **Description** | Generation of domains for different decision variables and other parameters based on the propagation of constraints. Transmission of this information in the form of fixed value of certain variables and/or additional constraints to the MP. |
| **Phase** | **P4** |
| **Name** | Merging MILP/MIP/IP model |
| **Description** | Merging files generated during the phases G1, G2 and G3 into one file. It is a model file format in LINGO system. |
| **Phase** | **P5** |
| **Name** | Solving MILP/MIP/IP model |
| **Description** | The solution model from the previous stage by LINGO. Generation of the report with the results and parameters of the solution. |

During this phase, the transformation was performed using the structure and properties of the model. This is an optional phase that depends on the modelled problem. The details of this phase will be presented in one of the illustrative examples in Section 4 (cost optimisation of supply chain).

CLP, constraint logic programming; IP, integer programming; MILP, mixed integer linear programming; MIP, mixed integer programming.

## 4 Illustrative examples

The proposed HSE environment was verified and tested for two illustrative examples. The first example is the authors' original model of cost optimisation of supply chain with multimodal transport (section A). The second is a two-echelon capacitated vehicle routing problem (2E-CVRP) model (section B). It is the known benchmark of a very large number of sets/instances of data and their solutions.

### A Cost optimisation of supply chain with multimodal transport

During the first stage, the model was formulated as a MILP problem [9, 10, 17] in order to test the proposed environment (Figs 1, 2) against the classical IP environment [22]. The next step involved the implementation and solving of the hybrid model. Indices, parameters and decision variables in the models together with their descriptions are provided in Table 2. The simplified structure of the supply chain network for this model, composed of producers, distributors and customers is presented in Fig. 5.

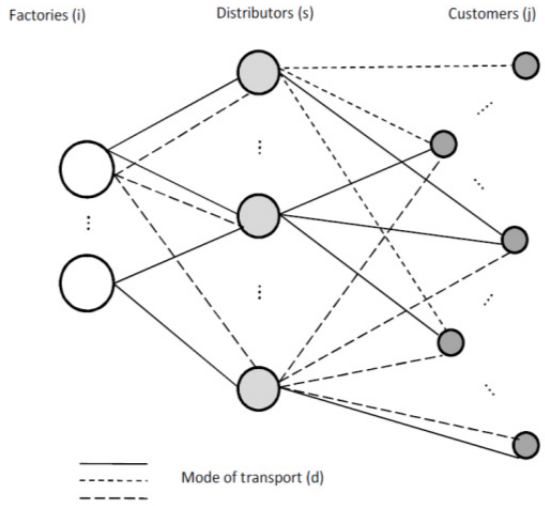


Figure 5. The simplified structure of the supply chain network

Table 2. Summary indices, parameters and decision variables

| Symbol | Description |
|---|---|
| **Indices** | |
| N | number of manufacturers/factories |
| M | number of delivery points/customers |
| E | number of distributors |
| O | number of product types |
| L | number of mode of transport |
| k | product type (k = 1, …0) |
| j | delivery point/customer/city (j = 1, … M) |
| i | manufacturer/factory (i = 1, … N) |
| s | distributor/distribution centre (s = 1,… E) |
| d | mode of transport (d = 1, … L) |
| **Input parameters** | |
| $F_s$ | the fixed cost of distributor/distribution centre s |
| $P_k$ | the area/volume occupied by product k |
| $V_s$ | distributor s maximum capacity/volume |
| $W_{i,k}$ | production capacity at factory i for product k |
| $C_{i,k}$ | the cost of product k at factory i |
| $R_{s,k}$ | if distributor s can deliver product k then $R_{sk} = 1$ $R_{s,k} = 1$, otherwise $R_{s,k} = 0$ |
| $Tp_{s,k}$ | the time needed for distributor s to prepare the shipment of product k |
| $Tc_{j,k}$ | the cut-off time of delivery to the delivery point/customer j of product k |
| $Z_{j,k}$ | customer demand/order j for product k |
| $Zt_d$ | the number of transport units using mode of transport d |
| $Pt_d$ | the capacity of transport unit using mode of transport d |
| $Tf_{i,s,d}$ | the time of delivery from manufacturer i to distributor s using mode of transport d |
| $Ka_{i,s,k,d}$ | the variable cost of delivery of product k from manufacturer i or distributor s using mode of transport d |
| $Ra_{i,s,d}$ | if manufacturer i can deliver to distributor s using mode of transport d then $Ra_{i,s,d} = 1$, otherwise $Ra_{i,s,d} = 0$ |
| $A_{i,s,d}$ | the fixed cost of delivery from manufacturer i to distributor s using mode of transport d |
| $Tm_{s,j,d}$ | the time of delivery from distributor s to customer j using mode of transport d |
| $Kb_{s,j,k,d}$ | the variable cost of delivery of product k from distributor s to customer j using mode of transport d |
| $Rb_{s,j,d}$ | if distributor s can deliver to customer j using mode of transport d then $Rb_{s,j,d} = 1$, otherwise $Rb_{s,j,d} = 0$ |
| $G_{s,j,d}$ | the fixed cost of delivery from distributor s to customer j using mode of transport d |
| $Od_d$ | the environmental cost of using mode of transport d |
| **Decision variables** | |
| $X_{i,s,k,d}$ | delivery quantity of product k from manufacturer i to distributor s using mode of transport d |
| $Y_{s,j,k,d}$ | delivery quantity of product k from distributor s to customer j using mode of transport d |

Table 2 (cont.). Summary indices, parameters and decision variables

| Symbol | Description |
|---|---|
| **Decision variables** | |
| $Xa_{i,s,d}$ | if delivery is from manufacturer i to distributor s using mode of transport d then $Xa_{i,s,d}=1$, otherwise $Xa_{i,s,d}=0$ |
| $Xb_{i,s,d}$ | the number of courses from manufacturer i to distributor s using mode of transport d |
| $Ya_{s,j,d}$ | if delivery is from distributor s to customer j using mode of transport d then $Ya_{s,j,d}=1$, otherwise $Ya_{s,j,d}=0$ |
| $Yb_{s,j,d}$ | the number of courses from distributor s to customer j using mode of transport d |
| $Tc_s$ | if distributor s participates in deliveries, then $Tc_s=1$, otherwise $Tc_s=0$ |
| **Values calculated** | |
| $Koa_{i,s,d}$ | the total cost of delivery from distributor s to customer j using mode of transport d |
| $Kog_{s,j,d}$ | the total cost of delivery from distributor s to customer j using mode of transport d |
| Cw | arbitrarily large constant (for example, te sum of all orders) |

The proposed models are the cost models that take into account three other types of parameters, i.e., the spatial parameters (area/volume occupied by the product, distributor capacity and capacity of transport unit), time (duration of delivery and service by distributor, etc.) and the transport mode. Multimodality in this example is understood as the possibility of using different modes of transport: railway, commercial vehicles, heavy trucks and so on.

The main assumptions made for the construction of these models were as follows:

- the shared information process in the supply chain consists of resources (capacity, versatility, costs), inventory (capacity, versatility, costs, time), production (capacity, versatility, costs), product (volume), transport (cost, mode, time), demand and so on,
- a part of the supply chain has the structure as in Fig. 5,
- the transport is multimodal (several modes of transport, a limited number of means of transport for each mode),
- the environmental aspects of use of transport modes are taken into account,
- different products are combined in one batch of transport,
- the cost of supplies is presented in the form of a function (in this approach, linear function of fixed and variable costs),
- models have linear or linear and logical (hybrid model) constraints,
- logical constraints of hybrid model allow the distribution of exclusively one of two selected products in the distribution centre and allow the production of exclusively one of two selected products in the factory.

**Objective function**

The objective function (1) defines the aggregate costs of the entire chain and consists of five elements. The first element comprises the fixed costs associated with the operation of the distributor involved in the delivery (e.g. distribution centre, warehouse). The second element corresponds to environmental costs of using various means of transport. Those costs are dependent on the number of courses of the given means of transport and, on the other hand, on the environmental levy, which in turn may depend on the use of fossil fuels and carbon dioxide emissions.

The third component determines the cost of the delivery from the manufacturer to the distributor. Another component is responsible for the costs of the delivery from the distributor to the end user (the store, the individual client, etc.). The last component of the objective function determines the cost of manufacturing the product by the given manufacturer.

Formulating the objective function in this manner allows comprehensive cost optimisation of various aspects of supply chain management. Each subset of the objective function with the same constrains provides a subset of the optimisation area and makes it much easier to search for a solution.

$$\sum_{s=1}^{E}(F_s\cdot Tc_s)+\sum_{d=1}^{L}Od_d\Big(\sum_{i=1}^{N}\sum_{s=1}^{E}Xb_{i,s,d}+\sum_{s=1}^{E}\sum_{j=1}^{M}Yb_{j,s,d}\Big)+\sum_{i=1}^{N}\sum_{s=1}^{E}\sum_{d=1}^{L}Koa_{i,s,d}+\sum_{s=1}^{E}\sum_{j=1}^{M}\sum_{d=1}^{L}Kog_{s,j,d}+\sum_{i=1}^{N}\sum_{k=1}^{O}\Big(C_{ik}\cdot\sum_{s=1}^{E}\sum_{d=1}^{L}X_{i,s,k,d}\Big) \quad (1)$$

**Constraints**

The model was based on constraints (2)–(24) Constraint (2) specifies that all deliveries of product *k* produced by the manufacturer *i* and delivered to all

distributors *s* using mode of transport *d* do not exceed the manufacturer's production capacity.

Constraint (3) covers all customer j demands for product k ($Z_{j,k}$) through the implementation of delivery by distributors s (the values of decision variables $Y_{i,s,k,d}$). The flow balance of each distributor s corresponds to constraint (4). The possibility of delivery is dependent on the distributor's technical capabilities – constraint (5). Time constraint (6) ensures the terms of delivery are met. Constraints (7a), (7b) and (8) guarantee deliveries with available transport taken into account. Constraints (9), (10) and (11) set values of decision variables based on binary variables $Tc_s$, $Xa_{i,s,d}$ and $Ya_{s,j,d}$. Dependencies (12) and (13) represent the relationship based on which the total costs are calculated. In general, these may be any linear functions. The remaining constraints (14)-(23) arise from the nature of the model (MILP).

Constraint (24) allows the distribution of exclusively one of the two selected products in the distribution centre s. Similarly, constraint (25) allows the production of exclusively one of the two selected products in the factory i.

Those constraints result from technological, marketing, sales or safety reasons. Therefore, some products cannot be distributed and/or produced together. The constraint can be re-used for different pairs of product k and for some of or all distribution centres s and factories i. A logical constraint like this cannot be easily implemented in a linear model. Only declarative application environments based on CSP make it possible to implement constraints such as (24) and (25).

Adding this type of constraints changes the model class. It is a hybrid model.

$$\sum_{s=1}^{E}\sum_{d=1}^{L} X_{i,s,k,d} R_{s,k} \le W_{i,k} \text{ for } i=1..N, k=1..O \tag{2}$$

$$\sum_{s=1}^{E}\sum_{d=1}^{L} (Y_{s,j,k,d} \cdot R_{s,k}) \ge Z_{j,k} \text{ for } j=1..M, k=1..O \tag{3}$$

$$\sum_{i=1}^{N}\sum_{d=1}^{L} X_{i,s,k,d} = \sum_{j=1}^{M}\sum_{d=1}^{L} Y_{s,j,k,d} \text{ for } s=1..E, k=1..O \tag{4}$$

$$\sum_{k=1}^{O} (P_k \cdot \sum_{i=1}^{N}\sum_{d=1}^{L} X_{i,s,k,d}) \le Tc_s \cdot V_s \text{ for } s=1..E \tag{5}$$

$$Xa_{i,s,d} \cdot Tf_{i,s,d} + Xa_{i,s,d} \cdot Tp_{s,k} + Ya_{s,j,d} \cdot Tm_{s,j,d} \le Tc_{j,k} \quad \text{for } i=1..N, s=1..E, j=1..M, k=1..O, d=1..L \tag{6}$$

$$Ra_{i,s,d} \cdot Xb_{i,s,d} \cdot Pt_d \ge X_{i,s,k,d} \cdot P_k \quad \text{for } i=1..N, s=1..E, k=1..O, d=1..L \tag{7a}$$

$$Rb_{s,j,d} \cdot Yb_{s,j,d} \cdot Pt_d \ge Y_{s,j,k,d} \cdot P_k \quad \text{for } s=1..E,\ j=1..M,\ k=1..O, d=1..L \tag{7b}$$

$$\sum_{i=1}^{N}\sum_{s=1}^{E} Xb_{i,s,d} + \sum_{j=1}^{M}\sum_{s=1}^{E} Yb_{j,s,d} \le Zt_d \text{ for } d=1..L \tag{8}$$

$$\sum_{i=1}^{N}\sum_{d=1}^{L} Xb_{i,s,d} \le CW \cdot Tc_s \text{ for } s=1..E \tag{9}$$

$$Xb_{i,s,d} \le CW \cdot Xa_{i,s,d} \text{ for } i=1..N, s=1..E, d=1..L \tag{10}$$

$$Yb_{s,j,d} \le CW \cdot Ya_{s,j,d} \text{ for } s=1..E, j=1..M, d=1..L \tag{11}$$

$$Koa_{i,s,d} = A_{i,s,d} \cdot Xb_{i,s,d} + \sum_{k=1}^{O} (Ka_{i,s,k,d} * X_{i,s,k,d}) \quad \text{for } i=1..N, s=1..E, d=1..L \tag{12}$$

$$Kog_{s,j,d} = G_{s,j,d} \cdot Yb_{j,s,d} + \sum_{k=1}^{O} Kb_{s,j,k,d} \cdot Y_{s,j,k,d} \quad \text{for } s=1..E, j=1..M, d=1..L \tag{13}$$

$$X_{i,s,k,d} \ge 0 \text{ for } i=1..N, s=1..E, k=1..0, d=1..L \tag{14}$$

$$Xb_{i,s,d} \ge 0 \text{ for } i=1..N, s=1..E, d=1..L \tag{15}$$

$$Yb_{s,j,d} \ge 0 \text{ for } s=1..E, j=1..M, d=1..L \tag{16}$$

$$X_{i,s,k,d} \in C \text{ for } i=1..N, s=1..E, k=1..0, d=1..L \tag{17}$$

$$Xb_{i,s,d} \in C \text{ for } i=1..N, s=1..E, d=1..L \tag{18}$$

$$Y_{s,j,k,d} \in C \text{ for } s=1..E, j=1..M, k=1..0, d=1..L \tag{19}$$

$$Yb_{s,j,d} \in C \text{ for } s=1..E, j=1..M, d=1..L, \tag{20}$$

$$Xa_{i,s,d} \in \{0,1\} \text{ for } i=1..N, s=1..E, d=1..L, \tag{21}$$

$$Ya_{s,j,d} \in \{0,1\} \text{ for } s=1..E, j=2..M, d=1..L, \tag{22}$$

$$Tc_s \in \{0,1\} \text{ for } s=1..E \tag{23}$$

$$\text{ExclusionD}(X_{i,s,k,d}, X_{i,s,l,d}, s) \text{ for } k \neq l,\ s=1..S \tag{24}$$

$$\text{ExclusionP}(X_{i,s,k,d}, X_{i,s,l,d}, i) \text{ for } k \neq l,\ i=1..N \tag{25}$$

**Model transformation**

Due to the nature of the decision problem (adding up decision variables and constraints involving a lot of variables), the constraint propagation efficiency de-

creases dramatically. Constraint propagation is one of the most important methods in CLP affecting the efficiency and effectiveness of the CLP and hybrid optimisation environment (Fig. 3, Table 1). For this reason, research into more efficient and more effective methods of constraint propagation was conducted. The results included different representation of the problem and the manner of its implementation.

The classical problem modelling in the CLP environment consists in building a set of predicates with parameters. Each CLP predicate has a corresponding multi-dimensional vector representation. While modelling both problems, quantities *i, s, k, d* and decision variable $X_{i,s,k,d}$ were vector parameters (Fig. 6a). As shown in Fig. 6b, for each vector instance, there are five values to be determined. They define the size of the delivery, factories, distributors involved in the delivery and the mode of transport.

[Z_n,P,M,D,F,Tu,Tu,Oq,X,T]

Fig. 6a Representation of the problem in the classical approach – vector definition

[[z_1,p1,m1,_,_,_,_,10,_,8],
[z_2,p1,m2,_,_,_,_,20,_,6],…]

Fig. 6b Representation of the problem in the classical approach – a set of vector instances in the process of finding a solution

The process of finding the solution may consist in using the constraint propagation methods, variable labelling and the backtracking mechanism. The number of parameters that must be specified/labelled in the given predicate/vector critically affect the quality of constraint propagation and the number of backtracks. In both models presented above, the classical problem representation included five parameters: i, s, k, d and $X_{i,s,k,d}$. Considering the domain size of each parameter, the process was complex and time-consuming. In addition, the above representation (Fig. 6a, 6b) arising from the structure of the problem is the cause of many backtracks.

Our idea involved the transformation of the problem by changing its representation without changing the very problem. All permissible routes were first generated based on the fixed data and a set of orders, and then the specific values of parameters i, s, k, d were assigned to each of the routes. In this way, only decision variables $X_{i,s,k,d}$ (deliveries) had to be specified (Fig. 7). This transformation fundamentally improved the efficiency of the constraint propagation and reduced the number of backtracks. A route model is a name adopted for the models that underwent the transformation.

[[name_1,f1,p1,c1,m1,s1,s1,5,12,100,_],
[name_2,f1,p1,c1,m1,s1,s2,6,14,100,_],
[name_3,f1,p1,c1,m1,s2,s1,6,22,100,_],...]

Figure 7. Representation of the problem in the novel approach – a set of feasible routes

Symbols necessary to understand both the representation of the problem and their descriptions are presented in Table 3.

Table 3. Symbols used in the representation of the problem

| Symbol | Description |
|---|---|
| Z_n | order number |
| P | products, $P\{p_1,p_2, \ldots ,p_o\}$ |
| M | customers, $M\{m_1,m_2, \ldots m_m\}$ |
| D | distributors, $D\{c_1,c_2, \ldots c_e\}$ |
| F | factories, $F\{f_1,f_2, \ldots f_n\}$ |
| Tu | transport unit, $Tu\{s_1,s_2, \ldots s_l\}$ |
| T | delivery time/period |
| Oq | order quantity |
| X | delivery quantity |
| Name_ | routes name-number |

**Decision-making support**

The proposed models can support decision-making in the following areas:

- the optimisation of total cost of the supply chain (objective function, decision variables – Appendix A2),
- the selection of the transport fleet number, capacity and modes for specific total costs,
- the sizing of distributor warehouses and the study of their impact on the overall costs,
- the selection of transport routes for optimal total cost.

Detailed studies of these topics are being conducted and will be described in our future articles. We use the hybrid approach to both modelling and solving.

## B Two-Echelon Capacitated Vehicle Routing Problem

The 2E-CVRP is proposed as a benchmark verifying the presented approach. The 2E-CVRP is an extension

of the classical capacitated vehicle routing problem (CVRP) where the delivery depot-customers pass through intermediate depots (called satellites). As in CVRP, the goal is to deliver goods to customers with known demands, minimising the total delivery cost with respect to vehicle capacity constraints. Multi-echelon systems presented in the literature usually explicitly consider the routing problem at the last level of the transportation system, while a simplified routing problem is considered at higher levels [18, 19, 23].

In 2E-CVRP, the freight delivery from the depot to the customers is managed by shipping the freight through intermediate depots. Thus, the transportation network is decomposed into two levels (Fig. 8): the first level connecting the depot (d) to intermediate depots (s) and the second one connecting the intermediate depots (s) to the customers (c). The objective is to minimise the total transportation cost of the vehicles involved in both levels. Constraints on the maximum capacity of the vehicles and the intermediate depots are considered, while the timing of the deliveries is ignored.

From a practical point of view, a 2E-CVRP system operates as follows (Fig. 8):

- freight arrives at an external zone, the depot, where it is consolidated into the first-level vehicles, unless it is already carried into a fully-loaded first-level vehicles,
- each first-level vehicle travels to a subset of satellites that will be determined by the model and then it will return to the depot,
- at a satellite, freight is transferred from first-level vehicles to second-level vehicles.

The mathematical model (MILP) was taken from [18]. Table 4 shows the parameters and decision variables of 2E-CVRP. Figure 8 shows an example of the 2E-CVRP transportation network.

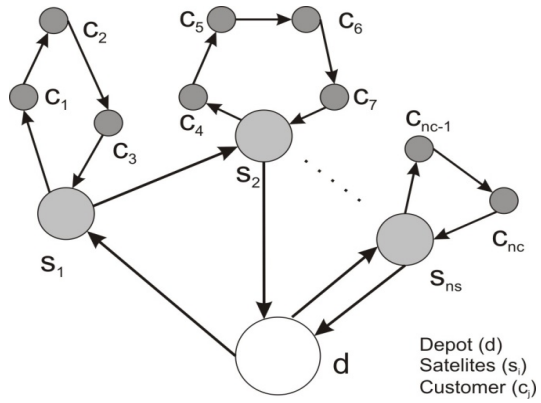


Figure 8. An example of two-echelon capacitated vehicle routing problem transportation network

The transformation of this model in the hybrid approach focused on the resizing of $Y_{k,i,j}$ decision variable by introducing additional imaginary volume of freight shipped from the satellite and re-delivered to it. Such transformation resulted in two facts. First of all, it forced the vehicle to return to the satellite from which it started its trip. Second, it reduced decision variable $Y_{k,i,j}$ to variable $Y_{i,j}$, which decreased the size of the combinatorial problem.

Table 4. Summary indices, parameters and decision variables

| Symbol | Description |
|---|---|
| **Indices** | |
| $n_s$ | number of satellites |
| $n_c$ | number of customers |
| $V_0 = \{v_o\}$ | depot |
| $V_s = \{v_{s1}, v_{s2}, ...v_{sn_s}\}$ | set of satellites |
| $V_c = \{v_{c1}, v_{c2}, ...v_{cn_c}\}$ | set of customers |
| **Input parameters** | |
| $M_1$ | number of the first-level satellites |
| $M_2$ | number of the second-level satellites |
| $K_1$ | capacity of the vehicles for the first level |
| $K_2$ | capacity of the vehicles for the second level |
| $d_i$ | demand required by customer i |
| $c_{i,j}$ | cost of the arc (i, j) |
| $s_k$ | cost of loading/unloading operations of a unit of freight in satellite k |
| **Decision variables** | |
| $X_{i,j}$ | an integer variable of the first-level routing is equal to the number of first-level vehicles using arc (i, j) |
| $Y_{k,i,j}$ | a binary variable of the second-level routing is equal to 1 if a second-level vehicle makes a route starting from satellite k and goes from node i to node j and 0 otherwise |
| $Q^1_{i,j}$ | the freight flow arc (i, j) for the first-level |
| $Q^2_{k,i,j}$ | the freight arc (i, j) where k represents the satellite where the freight is passing through |
| $z_{k,j}$ | a binary variable that is equal to 1 if the freight to be delivered to customer j is consolidated in satellite k and 0 otherwise |

$$\min \sum_{i,j\in V_0\cup V_s}(c_{i,j}\cdot X_{i,j})+\sum_{k\in V_s}\sum_{i,j\in V_s\cup V_c}(c_{i,j}\cdot Y_{k,i,j}) + \sum_{k\in V_s}(s_k\cdot Ds_k) \quad (1)$$

$$\sum_{i\in V_s} X_{0,i}\le M_1 \quad (2)$$

$$\sum_{j\in V_s\cup V_0, j\neq k} X_{j,k} = \sum_{i\in V_s\cup V_0, i\neq k} X_{k,i} \text{ for } k\in V_s\cup V_0 \quad (3)$$

$$\sum_{k\in V_s}\sum_{j\in V_c} Y_{k,k,j}\le M_2 \quad (4)$$

$$\sum_{i\in V_c, j\in V_c} Y_{k,i,j} = \sum_{i\in V_c, j\in V_c} Y_{k,j,i} \text{ for } k\in V_s \quad (5)$$

$$\sum_{i\in V_0\cup V_s, i\neq j} Q^1_{i,j} - \sum_{i\in V_s, i\neq j} Q^1_{j,i} = \begin{cases} Ds_j & j \text{ is not the deport} \\ \sum_{i\in V_c} -d_i & \text{otherwise} \end{cases} \text{ for } j\in V_s\cup V_0 \quad (6)$$

$$Q^1_{i,j}\le k_1\cdot X_{i,j} \text{ for } i,j\in V_s\cup V_0, i\neq j \quad (7)$$

$$\sum_{i\in V_s\cup V_c, i\neq j} Q^2_{k,i,j} - \sum_{i\in V_c, i\neq j} Q^2_{k,j,i} = \begin{cases} Z_{k,j}d_j & j \text{ is not a satelite} \\ -D_j & \text{otherwise} \end{cases} \text{ for } j\in V_c\cup V_S, k\in V_s \quad (8)$$

$$Q^2_{k,i,j}\le k_2\cdot Y_{k,i,j} \text{ for } i,j\in V_s\cup V_c, i\neq j, k\in V_s \quad (9)$$

$$\sum_{i\in V_s} Q^1_{i,V_0} = 0 \quad (10)$$

$$\sum_{j\in V_c} Q^2_{k,j,k} = 0 \text{ for } k\in V_s \quad (11)$$

$$Y_{k,i,j}\le Z_{k,j} \text{ for } i\in V_s\cup V_c, j\in V_c, k\in V_s \quad (12)$$

$$Y_{k,j,i}\le Z_{k,j} \text{ for } i\in V_s, j\in V_c, k\in V_s \quad (13)$$

$$\sum_{i\in V_s\cup V_c} Y_{k,i,j} = Z_{k,j} \text{ for } k\in V_s, j\in V_c, i\neq k \quad (14)$$

$$\sum_{i\in V_s} Y_{k,j,k} = Z_{k,j} \text{ for } k\in V_s, j\in V_c, i\neq k \quad (15)$$

$$\sum_{i\in V_s} Z_{i,j} = 1 \text{ for } j\in V_c \quad (16)$$

$$Y_{k,i,j}\le \sum_{l\in V_s\cup V_0} X_{k,l} \text{ for } k\in V_s, i,j\in V_c \quad (17)$$

$$Y_{k,i,j}\in\{0,1\}, Z_{k,l}\in\{0,1\} \text{ for } k\in V_s, i,j\in V_s\cup V_c, l\in V_c \quad (18)$$

$$X_{k,j}\in Z^+ \text{ for } k,j\in V_s\cup V_0 \quad (19)$$

$$Q^1_{i,j}\ge 0 \text{ for } i,j\in V_s\cup V_0; Q^2_{k,i,j}\ge 0 \text{ for } i,j\in V_s\cup V_c, k\in V_s \quad (20)$$

$$Ds_k = \sum_{l\in V_c}(d_j\cdot Z_{k,j}) \text{ for } k\in V_s$$

$$\sum_{i,j\in S_c} Y_{k,i,j}\le |S_c|-1 \text{ for } S_c\subset V_c, 2\le |S_c|\le |V_c|-2 \quad (21)$$

$$Q^2_{k,i,j}\le (k_2-d_j)\cdot Y_{k,i,j} \text{ for } i,j\in V_c, k\in V_s \quad (22)$$

$$Q^2_{k,i,j} - \sum_{l\in V_s} Q^2_{k,j,l}\le (k_2-d_j)\cdot Y_{k,i,j} \text{ for } i,j\in V_c, k\in V_s \quad (23)$$

## 5 Numerical experiments

In order to verify and evaluate the proposed approach, many numerical experiments were performed for both illustrative examples.

### A Cost optimisation of supply chain with multimodal transport

All the examples relate to the supply chain with two manufacturers (i = 1..2), three distributors (s = 1..3), five customers (j = 1..5), three modes of transport (d = 1..3) and 10 types of products (k = 1..10). Other parameter values are shown in Appendix A1. The first series of experiments were designed to show the advantages of the hybrid approach used.

The experiments began with six examples: E1, E2, E3, E4, E5 and E6 for the problem formulated in MILP (Section 4) [17]. Two approaches were used to implement the proposed model: mathematical programming (LINGO) and the hybrid approach (LINGO, Eclipse, transformation). The examples E1 .. E6 varied in terms of the number of orders (No). The set of all orders for calculation examples is given in Appendix A1. The experiments were conducted to optimise examples E7 and E8, which are implementations of the hybrid model (with logical constraints) in the hybrid approach.

The implementation of logic constraints for the hybrid model was as follows: product k = 5 cannot be distributed with product k = 6; product k = 2 cannot be distributed with product k = 8; and these products cannot be produced together. The results in the form of the objective function, computation time, number of discrete decision variables and constraints are shown in Table 5 and Appendix A2.

Table 5. The results of numerical examples for both approaches

| E(No) | MILP-LINGO | | | | MILP-Hybrid | | | |
|---|---|---|---|---|---|---|---|---|
| | Fc | T | V | C | Fc | T | V | C |
| E1(6) | 7764 | 4 | 1389 | 1405 | 7764 | 1 | 155 | 174 |
| E2(9) | 17043* | 600** | 1389 | 1567 | 17039 | 235 | 182 | 177 |
| E3(12) | 24106 | 600** | 1389 | 1729 | 24106 | 5 | 215 | 177 |
| E4(18) | 35772 | 600** | 1389 | 2053 | 35772 | 3 | 305 | 178 |
| E5(24) | 46481 | 600** | 1389 | 2377 | 46481 | 11 | 370 | 178 |
| E6(30) | 48946* | 600** | 1389 | 2701 | 48006 | 8 | 450 | 178 |

| P(No) | Hybrid-Hybrid | | | |
|---|---|---|---|---|
| | Fc | T | V | C |
| E7(12) | 24359 | 45 | 235 | 207 |
| E8(18) | 35792 | 136 | 325 | 208 |

| | |
|---|---|
| **Fc** | The optimal value of the objective function |
| **T** | Solution finding time |
| **V/C** | The number of integer variables/constraints |
| * | The feasible value of the objective function after the time T |
| ** | Calculation was stopped after T = 600s |

The analysis of the outcome indicates that the hybrid approach provided better results in terms of the time needed to find the solution in each case, and to obtain the optimal solution in some cases, which was impossible to do within the acceptable time limits using the traditional approaches.

## B Two-Echelon Capacitated Vehicle Routing Problem

For the final validation of the proposed hybrid approach, the benchmark (2E-CVRP) was selected. 2E-CVRP, a well described and widely discussed problem, corresponded with the issues to which our hybrid approach was applied.

The instances for computational examples were built from the existing instances for CVRP [24] denoted as E-n13-k4. All the instance sets can be downloaded from the website [25]. The instance set was composed of five small-sized instances with one depot, 12 customers and two satellites. The full instance consisted of 66 small-sized instances because the two satellites were placed over 12 customers in all 66 possible ways (number of combinations: 2 out of 12). All the instances had the same position for depot and customers, whose coordinates were the same as those of instance E-n13-k4. Small-sized instances differed in the choice of two customers who were also satellites (En13-k4-2 (1,3), En13-k4-6 (1,6), En13-k4-61 (9,10), etc.).

The analysis of the results for the benchmark instances demonstrates that the hybrid approach may be a superior approach to the classical mathematical programming. For all examples, the solutions were found 2–16 times faster than they are in the classical approach. As the presented benchmark was formulated as an MILP problem, the HSF was tested for the solution efficiency. Owing to the hybrid approach, the 2E-CVRP models can be extended over logical, non-linear and other constraints.

Table 6. The results of numerical examples for both approaches

| E-n13-k4 | MILP-LINGO | | | | MILP-Hybrid | | | |
|---|---|---|---|---|---|---|---|---|
| | Fc | T | V | C | Fc | T | V | C |
| En13-k4-13 | 288 | 600* | 368 | 1262 | 288 | 342 | 186 | 1024 |
| En13-k4-6 | 230 | 125 | 368 | 1262 | 230 | 55 | 186 | 1024 |
| En13-k4-9 | 244 | 153 | 368 | 1262 | 244 | 44 | 186 | 1024 |
| En13-k4-20 | 276 | 535 | 368 | 1262 | 276 | 32 | 186 | 1024 |
| En13-k4-61 | 338 | 6648 | 368 | 1262 | 338 | 407 | 186 | 1024 |

| | |
|---|---|
| **Fc** | The optimal value of the objective function |
| **T** | Time of finding solution |
| **V/C** | The number of integer variables/constraints |
| * | The feasible value of the objective function after the time T |

## 6 Conclusion and discussion on possible extension

The efficiency of the proposed approach is based on the reduction of the combinatorial problem and using the best properties of both environments. The hybrid approach (Tables 5, 6) makes it possible to find better solutions in the shorter time.

In addition to solving larger problems faster, the proposed approach provides virtually unlimited modelling options.

Therefore, the proposed solution is recommended for decision-making problems that have a structure similar to the presented models (Section 4). This structure is characterised by the constraints and objective function in which the decision variables are added together. Further work will focus on running the optimisation models with non-linear and logical constraints, multi-objective, uncertainty and so on in the hybrid optimisation framework.

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## APPENDIX A1

Table 7. Data for computational examples E1, E2, E3, E4, E5, E6, E7 and E8

| k | $V_k$ |
|---|---|
| P1 | 1 |
| P2 | 1 |
| P3 | 3 |
| P4 | 2 |
| P5 | 3 |
| P6 | 1 |
| P7 | 1 |
| P8 | 3 |
| P9 | 2 |
| P10 | 3 |

| j |
|---|
| 1 |
| 2 |
| 3 |
| 4 |
| 5 |

| i |
|---|
| F1 |
| F2 |

| s | $F_s$ | $V_s$ | |
|---|---|---|---|
| | | $E_1$,-$E_3$, $E_7$ | $E_4$,-$E_6$, $E_8$ |
| C1 | 600 | 200 | 800 |
| C2 | 700 | 200 | 800 |
| C3 | 900 | 200 | 1000 |

| d | $Pt_s$ | $Zt_s$ | | $Od_d$ |
|---|---|---|---|---|
| | | $E_1$,-$E_3$, $E_7$ | $E_4$, - $E_6$, $E_8$ | |
| S1 | 10 | 30 | 60 | 125 |
| S2 | 20 | 20 | 35 | 180 |
| S3 | 40 | 10 | 20 | 240 |

| i | s | d | $K_{i,s,d}$ | $T_{i,s,d}$ |
|---|---|---|---|---|
| F1 | C1 | S2 | 2 | 3 |
| F1 | C1 | S3 | 4 | 4 |
| F1 | C2 | S2 | 4 | 2 |
| F1 | C2 | S3 | 8 | 3 |
| F1 | C3 | S2 | 6 | 2 |
| F1 | C3 | S3 | 8 | 3 |

| i | k | $W_{i,k}$ | $C_{i,k}$ |
|---|---|---|---|
| F1 | P1 | 350 | 10 |
| F1 | P2 | 300 | 40 |
| F1 | P3 | 500 | 30 |
| F1 | P4 | 600 | 40 |
| F1 | P5 | 400 | 50 |
| F1 | P6 | 300 | 60 |

| | | | | |
|---|---|---|---|---|
| F2 | C1 | S2 | 5 | 4 |
| F2 | C1 | S3 | 7 | 4 |
| F2 | C2 | S2 | 2 | 6 |
| F2 | C2 | S3 | 4 | 7 |
| F2 | C3 | S2 | 2 | 6 |
| F2 | C3 | S3 | 3 | 6 |

| | | | |
|---|---|---|---|
| F2 | P5 | 400 | 50 |
| F2 | P6 | 300 | 60 |
| F2 | P7 | 400 | 70 |
| F2 | P8 | 500 | 80 |
| F2 | P9 | 600 | 90 |
| F2 | P10 | 650 | 90 |

| s | j | d | $K_{s,j,d}$ | $T_{s,j,d}$ | s | j | d | $K_{s,j,d}$ | $T_{s,j,d}$ |
|---|---|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 2 | 1 | C2 | M3 | S2 | 6 | 2 |
| C1 | M1 | S2 | 4 | 2 | C2 | M4 | S1 | 3 | 1 |
| C1 | M2 | S1 | 2 | 1 | C2 | M4 | S2 | 6 | 2 |
| C1 | M2 | S2 | 4 | 2 | C2 | M5 | S1 | 3 | 1 |
| C1 | M3 | S1 | 2 | 1 | C2 | M5 | S2 | 6 | 2 |
| C1 | M3 | S2 | 4 | 2 | C3 | M1 | S1 | 4 | 1 |
| C1 | M4 | S1 | 2 | 1 | C3 | M1 | S2 | 8 | 2 |
| C1 | M4 | S2 | 4 | 2 | C3 | M2 | S1 | 4 | 1 |
| C1 | M5 | S1 | 2 | 1 | C3 | M2 | S2 | 8 | 2 |
| C1 | M5 | S2 | 4 | 2 | C3 | M3 | S1 | 4 | 1 |
| C2 | M1 | S1 | 3 | 1 | C3 | M3 | S2 | 8 | 2 |
| C2 | M1 | S2 | 6 | 2 | C3 | M4 | S1 | 4 | 1 |
| C2 | M2 | S1 | 3 | 1 | C3 | M4 | S2 | 8 | 2 |
| C2 | M2 | S2 | 6 | 2 | C3 | M5 | S1 | 4 | 1 |
| C2 | M3 | S1 | 3 | 1 | C3 | M5 | S2 | 8 | 2 |

| k | i | k |
|---|---|---|
| P5 | F1 | P6 |
| P5 | F2 | P6 |
| P2 | F1 | P8 |
| P2 | F2 | P8 |

| k | s | k |
|---|---|---|
| P5 | C1 | P6 |
| P5 | C2 | P6 |
| P5 | C3 | P6 |
| P2 | C1 | P8 |
| P2 | C2 | P8 |
| P2 | C3 | P8 |

| s | k | $T_{s,k}$ | s | k | $T_{s,k}$ | s | k | $T_{s,k}$ |
|---|---|---|---|---|---|---|---|---|
| C1 | P1 | 2 | C2 | P1 | 1 | C3 | P1 | 3 |
| C1 | P2 | 2 | C2 | P2 | 1 | C3 | P2 | 3 |
| C1 | P3 | 2 | C2 | P3 | 1 | C3 | P3 | 3 |
| C1 | P4 | 2 | C2 | P4 | 1 | C3 | P4 | 3 |
| C1 | P5 | 2 | C2 | P5 | 1 | C3 | P5 | 3 |
| C1 | P6 | 2 | C2 | P6 | 1 | C3 | P6 | 3 |
| C1 | P7 | 2 | C2 | P7 | 1 | C3 | P7 | 3 |
| C1 | P8 | 2 | C2 | P8 | 1 | C3 | P8 | 3 |
| C1 | P9 | 2 | C2 | P9 | 1 | C3 | P9 | 3 |
| C1 | P10 | 2 | C2 | P10 | 1 | C3 | P10 | 3 |

| Name | k | j | $T_{j,k}$ | $Z_{j,k}$ | Name | k | j | $T_{j,k}$ | $Z_{j,k}$ |
|---|---|---|---|---|---|---|---|---|---|
| Z_01 | p1 | m1 | 8 | 10 | Z_11 | p1 | m3 | 8 | 15 |
| Z_02 | p2 | m2 | 12 | 10 | Z_12 | p2 | m4 | 12 | 20 |
| Z_03 | p3 | m3 | 10 | 25 | Z_13 | p3 | m5 | 10 | 25 |
| Z_04 | p4 | m4 | 8 | 30 | Z_14 | p4 | m1 | 8 | 30 |
| Z_05 | p5 | m5 | 12 | 10 | Z_15 | p5 | m2 | 12 | 30 |
| Z_06 | p6 | m1 | 8 | 15 | Z_16 | p6 | m3 | 8 | 15 |
| Z_07 | p7 | m2 | 12 | 20 | Z_17 | p7 | m4 | 12 | 20 |
| Z_08 | p8 | m3 | 10 | 25 | Z_18 | p8 | m5 | 10 | 25 |
| Z_09 | p9 | m4 | 8 | 30 | Z_19 | p9 | m1 | 8 | 30 |
| Z_10 | p10 | m5 | 12 | 30 | Z_20 | p10 | m2 | 12 | 35 |

## APPENDIX A2

Table 8. Results of optimisation for computational examples E1, E2, E3, E4, E5, E6, E7 and E8

**Example E1 $Fc^{opt}$ = 7764**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S2 | 10.00 | 10.00 |
| Z_02 | F1 | P2 | C1 | M2 | S3 | S1 | 10.00 | 10.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | 25.00 | 25.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | 30.00 | 30.00 |
| Z_05 | F1 | P5 | C1 | M5 | S3 | S2 | 10.00 | 10.00 |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S1 | 15.00 | 10.00 |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S2 | | 5.00 |

| i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|
| F1 | C1 | S3 | 5 |

| s | J | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 1 | C1 | M3 | S2 | 4 |
| C1 | M1 | S2 | 1 | C1 | M4 | S2 | 3 |
| C1 | M2 | S1 | 1 | C1 | M5 | S2 | 2 |

**Example E2 $Fc^{opt}$ = 17039**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S2 | 10.00 | 10.00 |
| Z_02 | F1 | P2 | C2 | M2 | S3 | S1 | 10.00 | 10.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | 16.00 | 16.00 |
| Z_03 | F1 | P3 | C2 | M3 | S3 | S2 | 9.00 | 9.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | 30.00 | 30.00 |
| Z_05 | F1 | P5 | C2 | M5 | S3 | S2 | 1.00 | 10.00 |
| Z_05 | F2 | P5 | C2 | M5 | S3 | S2 | 9.00 | |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S1 | 2.00 | 5.00 |
| Z_06 | F2 | P6 | C1 | M1 | S3 | S1 | 13.00 | |
| Z_06 | F2 | P6 | C1 | M1 | S3 | S2 | | 10.00 |
| Z_07 | F2 | P7 | C2 | M2 | S3 | S2 | 20.00 | 20.00 |
| Z_08 | F2 | P8 | C1 | M3 | S3 | S2 | 2.00 | 2.00 |
| Z_08 | F2 | P8 | C2 | M3 | S3 | S2 | 23.00 | 23.00 |
| Z_09 | F2 | P9 | C1 | M4 | S3 | S2 | 30.00 | 30.00 |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S3 | 3 | F2 | C1 | S3 | 2 |
| F1 | C2 | S3 | 1 | F2 | C2 | S3 | 3 |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 1 | C2 | M2 | S1 | 1 |
| C1 | M1 | S2 | 1 | C2 | M2 | S2 | 1 |
| C1 | M3 | S2 | 3 | C2 | M3 | S2 | 5 |
| C1 | M4 | S2 | 6 | C2 | M5 | S2 | 2 |

**Example E3 $Fc^{opt}$ = 24106**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S1 | 25.00 | 10.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S1 | | 15.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S2 | | |
| Z_02 | F1 | P2 | C1 | M2 | S3 | S1 | 30.00 | 10.00 |
| Z_12 | F1 | P2 | C1 | M4 | S3 | S2 | | 20.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S1 | 25.00 | 3.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | | 22.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S1 | 30.00 | 20.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | | 10.00 |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S1 | 10.00 | 10.00 |
| Z_06 | F2 | P6 | C2 | M1 | S2 | S1 | 5.00 | 5.00 |
| Z_05 | F2 | P5 | C3 | M5 | S3 | S2 | 10.00 | 10.00 |
| Z_07 | F2 | P7 | C3 | M2 | S3 | S2 | 20.00 | 20.00 |
| Z_08 | F2 | P8 | C2 | M3 | S2 | S1 | 5.00 | 5.00 |
| Z_08 | F2 | P8 | C2 | M3 | S3 | S2 | 20.00 | 20.00 |
| Z_09 | F2 | P9 | C2 | M4 | S2 | S1 | 30.00 | 30.00 |
| Z_10 | F2 | P10 | C2 | M5 | S3 | S2 | 20.00 | 20.00 |
| Z_10 | F2 | P10 | C3 | M5 | S3 | S2 | 10.00 | 10.00 |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S3 | 5 | F2 | C2 | S3 | 3 |
| F2 | C2 | S2 | 4 | F2 | C3 | S3 | 2 |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 2.000000 | C2 | M3 | S1 | 2.000000 |
| C1 | M2 | S1 | 1.000000 | C2 | M3 | S2 | 3.000000 |
| C1 | M3 | S1 | 1.000000 | C2 | M4 | S1 | 6.000000 |
| C1 | M3 | S2 | 4.000000 | C2 | M5 | S2 | 3.000000 |
| C1 | M4 | S1 | 4.000000 | C3 | M2 | S2 | 1.000000 |
| C1 | M4 | S2 | 2.000000 | C3 | M5 | S2 | 3.000000 |
| C2 | M1 | S1 | 1.000000 | | | | |

**Example E4 $Fc^{opt}$ = 35772**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S1 | 25.00 | 7.00 |
| Z_01 | F1 | P1 | C1 | M1 | S3 | S2 | | 3.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S2 | | 15.00 |
| Z_02 | F1 | P2 | C1 | M2 | S3 | S2 | 30.00 | 10.00 |
| Z_12 | F1 | P2 | C1 | M4 | S3 | S2 | | 20.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | 50.00 | 25.00 |
| Z_13 | F1 | P3 | C1 | M5 | S3 | S2 | | 25.00 |
| Z_14 | F1 | P4 | C1 | M1 | S3 | S1 | 60.00 | 4.00 |
| Z_14 | F1 | P4 | C1 | M1 | S3 | S2 | | 26.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | | 30.00 |
| Z_15 | F1 | P5 | C1 | M2 | S3 | S2 | 40.00 | 30.00 |
| Z_05 | F1 | P5 | C1 | M5 | S3 | S2 | | 10.00 |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S1 | 30.00 | 15.00 |
| Z_16 | F1 | P6 | C1 | M3 | S3 | S2 | | 15.00 |
| Z_17 | F2 | P7 | C1 | M4 | S3 | S1 | 20.00 | 20.00 |
| Z_07 | F2 | P7 | C2 | M2 | S2 | S2 | 20.00 | 20.00 |
| Z_08 | F2 | P8 | C1 | M3 | S3 | S2 | 50.00 | 25.00 |
| Z_18 | F2 | P8 | C1 | M5 | S3 | S2 | | 25.00 |
| Z_09 | F2 | P9 | C1 | M4 | S3 | S2 | 30.00 | 30.00 |
| Z_10 | F2 | P10 | C1 | M5 | S3 | S1 | 30.00 | 30.00 |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S3 | 12.00 | F2 | C2 | S2 | 1.00 |
| F2 | C1 | S3 | 8.00 | | | | |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 3.00 | C1 | M4 | S2 | 7.00 |
| C1 | M1 | S2 | 3.00 | C1 | M5 | S1 | 9.00 |
| C1 | M2 | S2 | 5.00 | C1 | M5 | S2 | 9.00 |
| C1 | M3 | S2 | 9.00 | C2 | M2 | S2 | 1.00 |
| C1 | M4 | S1 | 2.00 | | | | |

**Example E5 $Fc^{opt}$ = 46481**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S2 | 27.00 | 10.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S1 | | 2.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S2 | | 13.00 |
| Z_21 | F1 | P1 | C1 | M5 | S3 | S1 | | 2.00 |
| Z_20 | F2 | P10 | C1 | M2 | S3 | S2 | 31.00 | 1.00 |
| Z_10 | F2 | P10 | C1 | M5 | S3 | S1 | | 30.00 |
| Z_20 | F2 | P10 | C2 | M2 | S2 | S1 | 21.00 | 34.00 |
| Z_20 | F2 | P10 | C2 | M2 | S3 | S1 | 13.00 | |
| Z_02 | F1 | P2 | C1 | M1 | S3 | S2 | 31.00 | 1.00 |
| Z_02 | F1 | P2 | C1 | M2 | S3 | S2 | | 10.00 |
| Z_12 | F1 | P2 | C1 | M4 | S3 | S1 | | 20.00 |
| Z_23 | F1 | P3 | C1 | M4 | S2 | S1 | 2.00 | 1.00 |
| Z_03 | F1 | P3 | C1 | M3 | S2 | S2 | | 25.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | 50 | |
| Z_23 | F1 | P3 | C1 | M4 | S3 | S1 | | 1.00 |
| Z_13 | F1 | P3 | C1 | M5 | S3 | S1 | | 2.00 |
| Z_13 | F1 | P3 | C1 | M5 | S3 | S2 | | 23.00 |
| Z_04 | F1 | P4 | C1 | M4 | S2 | S1 | 6.00 | 12.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S1 | 55.00 | |
| Z_14 | F1 | P4 | C1 | M1 | S3 | S2 | | 30.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | | 18.00 |
| Z_24 | F1 | P4 | C1 | M5 | S3 | S1 | | 1.00 |
| Z_15 | F1 | P5 | C1 | M2 | S3 | S1 | 40.00 | 10.00 |
| Z_15 | F2 | P5 | C1 | M2 | S3 | S1 | | |
| Z_15 | F1 | P5 | C1 | M2 | S3 | S2 | | 20.00 |
| Z_05 | F1 | P5 | C1 | M5 | S3 | S1 | | 10.00 |
| Z_16 | F1 | P6 | C1 | M3 | S2 | S1 | 17.00 | 15.00 |
| Z_06 | F1 | P6 | C1 | M1 | S2 | S2 | | 3.00 |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S2 | 5.00 | |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S1 | | 4.00 |
| Z_06 | F2 | P6 | C2 | M1 | S2 | S1 | 8.00 | 8.00 |
| Z_07 | F2 | P7 | C1 | M2 | S3 | S1 | 12.00 | 10.00 |
| Z_07 | F2 | P7 | C1 | M2 | S3 | S2 | | 2.00 |
| Z_17 | F2 | P7 | C2 | M4 | S2 | S2 | 27.00 | 20.00 |
| Z_07 | F2 | P7 | C2 | M2 | S2 | S1 | | 8.00 |
| Z_07 | F2 | P7 | C2 | M2 | S3 | S1 | 1.00 | |
| Z_08 | F2 | P8 | C1 | M3 | S3 | S1 | 40.00 | 21.00 |
| Z_08 | F2 | P8 | C1 | M3 | S3 | S2 | | 4.00 |
| Z_08 | F2 | P8 | C1 | M5 | S3 | S2 | | 15.00 |
| Z_18 | F2 | P8 | C2 | M5 | S2 | S1 | 10.00 | 10.00 |
| Z_01 | F2 | P9 | C1 | M1 | S3 | S1 | 46.00 | 13.00 |
| Z_19 | F2 | P9 | C1 | M1 | S3 | S2 | | 3.00 |
| Z_09 | F2 | P9 | C1 | M4 | S3 | S2 | | 30.00 |
| Z_19 | F2 | P9 | C2 | M1 | S2 | S1 | 14.00 | 14.00 |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S2 | 2.00 | F2 | C2 | S2 | 8.00 |
| F1 | C1 | S3 | 11.00 | F2 | C2 | S3 | 1.00 |
| F2 | C1 | S3 | 8.00 | | | | |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 3.000000 | C1 | M4 | S2 | 5.000000 |
| C1 | M1 | S2 | 4.000000 | C1 | M5 | S1 | 13.00000 |
| C1 | M2 | S1 | 4.000000 | C1 | M5 | S2 | 6.000000 |
| C1 | M2 | S2 | 4.000000 | C2 | M1 | S1 | 4.000000 |
| C1 | M3 | S1 | 8.000000 | C2 | M2 | S1 | 11.00000 |
| C1 | M3 | S2 | 5.000000 | C2 | M4 | S2 | 1.000000 |
| C1 | M4 | S1 | 5.000000 | C2 | M5 | S1 | 3.000000 |

**Example E6 $Fc^{opt}$ = 48006**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S2 | S2 | 10.00 | 10.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S1 | 17.00 | 15.00 |
| Z_21 | F1 | P1 | C1 | M5 | S3 | S1 | | 2.00 |
| Z_02 | F1 | P2 | C1 | M2 | S2 | S1 | 10.00 | 10.00 |
| Z_22 | F1 | P2 | C1 | M1 | S3 | S2 | 21.00 | 1.00 |
| Z_12 | F1 | P2 | C1 | M4 | S3 | S1 | | 20.00 |
| Z_13 | F1 | P3 | C1 | M5 | S2 | S1 | 25.00 | 25.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S1 | 27.00 | 25.00 |
| Z_23 | F1 | P3 | C1 | M4 | S3 | S1 | | 2.00 |
| Z_04 | F1 | P4 | C1 | M4 | S2 | S1 | 4.00 | 1.00 |
| Z_24 | F1 | P4 | C1 | M5 | S2 | S1 | | 1.00 |
| Z_04 | F1 | P4 | C1 | M4 | S2 | S2 | 29.00 | |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | 57.00 | |
| Z_14 | F1 | P4 | C1 | M1 | S3 | S2 | | 30.00 |
| Z_25 | F1 | P5 | C1 | M3 | S2 | S1 | 2.00 | 1.00 |
| Z_05 | F1 | P5 | C1 | M5 | S2 | S1 | 8.00 | |
| Z_05 | F1 | P5 | C1 | M5 | S3 | S1 | 37.00 | |
| Z_15 | F1 | P5 | C1 | M2 | S3 | S1 | | 30.00 |
| Z_05 | F2 | P5 | C2 | M5 | S2 | S2 | 13.00 | 2.00 |
| Z_26 | F1 | P6 | C1 | M5 | S2 | S1 | | 1.00 |
| Z_06 | F1 | P6 | C1 | M1 | S2 | S2 | | 1.00 |
| Z_06 | F1 | P6 | C1 | M1 | S2 | S1 | 10.00 | |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S1 | 16.00 | |
| Z_16 | F1 | P6 | C1 | M3 | S3 | S2 | | 15.00 |
| Z_06 | F2 | P6 | C2 | M1 | S2 | S1 | 6.00 | 4.00 |
| Z_26 | F2 | P6 | C2 | M5 | S2 | S1 | | 2.00 |
| Z_07 | F2 | P7 | C1 | M2 | S3 | S1 | 35.00 | 18.00 |
| Z_17 | F2 | P7 | C1 | M4 | S3 | S1 | | 2.00 |
| Z_17 | F2 | P7 | C1 | M4 | S3 | S2 | | 15.00 |
| Z_07 | F2 | P7 | C2 | M2 | S2 | S1 | 2.00 | 2.00 |
| Z_27 | F2 | P7 | C2 | M3 | S3 | S2 | 5.00 | 2.00 |
| Z_17 | F2 | P7 | C2 | M4 | S3 | S1 | | 3.00 |
| Z_08 | F2 | P8 | C1 | M3 | S3 | S1 | 21.00 | 19.00 |
| Z_18 | F2 | P8 | C1 | M5 | S3 | S1 | | 2.00 |
| Z_08 | F2 | P8 | C2 | M3 | S2 | S2 | 19.00 | 6.00 |
| Z_28 | F2 | P8 | C2 | M4 | S2 | S1 | | 2.00 |
| Z_18 | F2 | P8 | C2 | M5 | S2 | S2 | 23.00 | |
| Z_18 | F2 | P8 | C2 | M5 | S3 | S2 | 12.00 | |
| Z_19 | F2 | P9 | C1 | M1 | S3 | S2 | 60.00 | 30.00 |
| Z_09 | F2 | P9 | C1 | M4 | S3 | S2 | | 30.00 |
| Z_29 | F2 | P9 | C2 | M2 | S2 | S1 | 2.00 | 2.00 |
| Z_20 | F2 | P10 | C1 | M2 | S3 | S1 | 34.00 | 34.00 |
| Z_30 | F2 | P10 | C2 | M1 | S2 | S1 | 7.00 | 2.00 |
| Z_20 | F2 | P10 | C2 | M2 | S2 | S1 | | 1.00 |
| Z_10 | F2 | P10 | C2 | M5 | S2 | S1 | | 2.00 |
| Z_10 | F2 | P10 | C2 | M5 | S2 | S2 | | 28.00 |
| Z_10 | F2 | P10 | C2 | M5 | S3 | S2 | 26.00 | |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S2 | 6.00 | F2 | C2 | S2 | 5.00 |
| F1 | C1 | S3 | 9.00 | F2 | C2 | S3 | 3.00 |
| F2 | C1 | S3 | 8.00 | | | | |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 1.00 | C1 | M5 | S1 | 11.00 |
| C1 | M1 | S2 | 7.00 | C2 | M1 | S1 | 1.00 |
| C1 | M2 | S1 | 22.00 | C2 | M2 | S1 | 1.00 |
| C1 | M3 | S1 | 15.00 | C2 | M3 | S2 | 1.00 |
| C1 | M3 | S2 | 1.00 | C2 | M4 | S1 | 1.00 |
| C1 | M4 | S1 | 3.00 | C2 | M5 | S1 | 1.00 |
| C1 | M4 | S2 | 7.00 | C2 | M5 | S2 | 8.00 |

**Example E7 $Fc^{opt}$ = 24359**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S1 | 5.000 | 5.000 |
| Z_01 | F1 | P1 | C2 | M1 | S2 | S1 | 5.00 | 5.00 |
| Z_11 | F1 | P1 | C2 | M3 | S2 | S2 | 15.00 | 15.00 |
| Z_02 | F1 | P2 | C1 | M2 | S3 | S1 | 10.00 | 10.00 |
| Z_12 | F1 | P2 | C1 | M4 | S3 | S2 | 20.00 | 20.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | 25.00 | 25.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | 30.00 | 30.00 |
| Z_05 | F1 | P5 | C1 | M5 | S3 | S1 | 10.00 | 10.00 |
| Z_06 | F2 | P6 | C2 | M1 | S2 | S1 | 15.00 | 15.00 |
| Z_07 | F2 | P7 | C3 | M2 | S3 | S2 | 20.00 | 20.00 |
| Z_08 | F2 | P8 | C2 | M3 | S3 | S2 | 15.00 | 15.00 |
| Z_08 | F2 | P8 | C3 | M3 | S3 | S1 | 10.00 | 10.00 |
| Z_09 | F2 | P9 | C2 | M4 | S2 | S1 | 30.00 | 30.00 |
| Z_10 | F2 | P10 | C2 | M5 | S2 | S2 | 1.00 | 20.00 |
| Z_10 | F2 | P10 | C2 | M5 | S3 | S2 | 19.00 | |
| Z_10 | F2 | P10 | C3 | M5 | S3 | S1 | 10.00 | 10.00 |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S3 | 5 | F2 | C2 | S3 | 33 |
| F1 | C2 | S2 | 1 | F2 | C2 | S3 | 2 |
| F2 | C2 | S2 | 4 | | | | |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S1 | 1.00 | C2 | M3 | S2 | 3.00 |
| C1 | M2 | S1 | 1.00 | C2 | M4 | S1 | 6.00 |
| C1 | M3 | S2 | 4.00 | C2 | M5 | S2 | 3.00 |
| C1 | M4 | S2 | 4.00 | C3 | M2 | S2 | 1.00 |
| C1 | M5 | S1 | 3.00 | C3 | M3 | S1 | 3.00 |
| | M1 | S1 | 2.00 | C3 | M5 | S1 | 3.00 |

**Example E8 $Fc^{opt}$ = 24359**

| Name | i | k | s | j | d1 | d2 | $X_{iskd1}$ | $Y_{sjkd2}$ |
|---|---|---|---|---|---|---|---|---|
| Z_01 | F1 | P1 | C1 | M1 | S3 | S2 | 19.00 | 4.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S1 | | 1.00 |
| Z_11 | F1 | P1 | C1 | M3 | S3 | S2 | | 14.00 |
| Z_01 | F1 | P1 | C2 | M1 | S3 | S1 | 6.00 | 6.00 |
| Z_10 | F2 | P10 | C1 | M5 | S3 | S2 | 30.00 | 30.00 |
| Z_02 | F1 | P2 | C2 | M2 | S3 | S2 | 30.00 | 10.00 |
| Z_12 | F1 | P2 | C2 | M4 | S3 | S2 | | 20.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S1 | 50.00 | 3.00 |
| Z_03 | F1 | P3 | C1 | M3 | S3 | S2 | | 22.00 |
| Z_13 | F1 | P3 | C1 | M5 | S3 | S2 | | 25.00 |
| Z_14 | F1 | P4 | C1 | M1 | S3 | S2 | 58.00 | 28.00 |
| Z_04 | F1 | P4 | C1 | M4 | S3 | S2 | | 30.00 |
| Z_14 | F1 | P4 | C2 | M1 | S3 | S1 | 2.00 | 2.00 |
| Z_15 | F2 | P5 | C2 | M2 | S2 | S2 | 6.00 | 30.00 |
| Z_15 | F2 | P5 | C2 | M2 | S3 | S2 | 34.00 | |
| Z_05 | F2 | P5 | C2 | M5 | S3 | S1 | | 10.00 |
| Z_06 | F1 | P6 | C1 | M1 | S3 | S2 | 30.00 | 15.00 |
| Z_16 | F1 | P6 | C1 | M3 | S3 | S1 | | 15.00 |
| Z_17 | F2 | P7 | C1 | M4 | S3 | S2 | 20.00 | 20.00 |
| Z_07 | F2 | P7 | C2 | M2 | S2 | S2 | 2.00 | 20.00 |
| Z_07 | F2 | P7 | C2 | M2 | S3 | S2 | 18.00 | |
| Z_08 | F2 | P8 | C1 | M3 | S3 | S1 | 50.00 | 25.00 |
| Z_18 | F2 | P8 | C1 | M5 | S3 | S2 | | 25.00 |
| Z_09 | F2 | P9 | C1 | M4 | S3 | S2 | 30.00 | 30.00 |

| i | s | d | $Xb_{i,s,d}$ | i | s | d | $Xb_{i,s,d}$ |
|---|---|---|---|---|---|---|---|
| F1 | C1 | S3 | 8.00 | F2 | C2 | S2 | 1.00 |
| F1 | C2 | S3 | 1.00 | F2 | C2 | S3 | 3.00 |
| F2 | C1 | S3 | 8.00 | | | | |

| s | j | d | $Yb_{s,j,d}$ | s | j | d | $Yb_{s,j,d}$ |
|---|---|---|---|---|---|---|---|
| C1 | M1 | S2 | 4.00 | C2 | M1 | S1 | 1.00 |
| C1 | M3 | S1 | 10.00 | C2 | M2 | S2 | 6.00 |
| C1 | M3 | S2 | 4.00 | C2 | M4 | S2 | 1.00 |
| C1 | M4 | S2 | 7.00 | C2 | M5 | S1 | 3.00 |
| C1 | M5 | S2 | 12.00 | | | | |

# IMPLEMENTATION OF ENTERPRISE SYSTEMS AS A STRATEGIC MOVE FOR STRENGTHENING A COMPANY'S COMPETITIVE ADVANTAGE

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***Abstract:*** This article discusses how the restructuring linked with broadly defined informatisation program can be used to gain a strategic competitive advantage in business. This problem is illustrated with an example representing the introduction of information technologies in the Municipal Transport Company (Miejskie Przedsiębiorstwo Komunikacyjne), as well as analysis and evaluation of the implementation of human resource management system. The analysis was carried out in the operational and strategic areas.

***Keywords***: reducing costs, improving work organisation, storage resources control, applicant tracking systems, comprehensive computerisation, implementation of management information system.

## 1 Introduction

The main objective of economic modern enterprise – in a market economy – is primarily to maximise company is obliged to effectively utilise the available fixed assets, financial resources and employees' potential or analyse the environment in which it operates.

Continuous micro- and macroeconomic analysis makes the company in the development process sustain growth, adapting functions, objectives and tasks, and organisation and management methods to changing business conditions. Competitive business should have internal ability and flexibility to adapt to changing operating conditions and obtain the specific benefits of this process.

The modern concept of creating a competitive advantage puts special emphasis on the need for skilful use of acquired knowledge and resources, and effective use of information technology (IT) in management decision-making processes [5]. IT supports the managerial decision-making process based on the various data sets, analysis, opinions, or advisory studies and reports.

Enterprise system strategy is the hierarchically highest structured component of management system and is characterised by high task–information dynamics [12]. An inherent element of the IT strategy is the integration of hardware infrastructure and telecommunications systems supporting management processes and operating and database environments.

Enterprise systems integration is possible through the implementation of complex and multifunctional packages of Enterprise Resource Planning (ERP). ERP system is a suite of integrated, highly efficient and multi-user applications built for the comprehensive management of manufacturing industrial company.

ERP system, subject to continuous improvement and evolution, has become the most widely used tool for production planning and control in large and medium-sized enterprises (business activities of 70% computerised industrial enterprises in the developed countries of Western Europe are based on computer systems compliant with ERP).

ERP system covers core business processes of production and distribution that integrates various company departments, facilitates information flow between all business functions and ensures quick response to the changes in demand. This information is updated in real-time and available at the time of making decision (for systems operating online).

Enterprise systems implementation will not only eliminate data reduction and reduce a significant number of errors (resulting from repeated entries of the same data into the system by different people) but also allows implementing different configuration processes developed on the basis of a full analysis of the system.

Introduction of enterprise systems supporting the company management results in measurable economic benefits that include:

- reducing costs by eliminating data redundancy, reducing operational activities through the implementation of process management model, as well as the automation procedures for monitoring and control of material resources,

- improving work organisation and the use of new methods of quality control up to the normative standards of ISO 9000 and ISO 14000, which is dictated by the applied implementation methodology and logic of the system,
- integration of procedures and functions, standardisation of source documents formsand the development of document management procedures (document flow project, control access rights, archive policy),
- access capability to real-time information about current economic events, current analysis of selected economic indicators (i.e., liquidity, profitability, inventory levels, settlements),
- control of accounts receivable and liabilities, the implementation of mechanisms for recipient monitoring and suspension of the execution of orders in case of arrears in payment (the ability to define for each client the loan amount and payment period),
- storage resources control, the possibility of transfer of materials between warehouses, automated monitoring of inventory and raw materials, notification of the need to supplement them,
- implementation of management information system, the ability to conduct multi-criteria analysis of operational and financial data (see [4, 8.10]); implementation of enterprise systems must be closely linked and correlated with the methodology of restructuring changes implementation.

In the implementation of MRP/ERP systems, the assessment of the degree of compromise between the package functionality and its susceptibility to modifications and changes and the need for the restructuring in the company are very important.

At present, the technology of modern enterprise systems allows them to be adapted to the specific nature and needs of a particular company. However, the costs of implementing, testing, documentation and maintenance of these changes have a significant impact on the budget of the project.

Any changes in standard software architecture also increase the risk of the whole project.

## 2 The concept of the methodical implementation of the information system project supporting the staff management at the Municipal Transport Company (MTC)

### 2.1 Definition of the project, purpose and scope of implementation

Changes in the passenger transport market, in particular, demonopolisation of the market and introduction of competition rules in the selection of particular lines operators, have forced introduction of restructuring changes in national communication companies. The strategic objective of the broader restructuring is to improve the quality of services, cost reduction and reorganisation of management processes. In the implementation of restructuring and change projects, fully effective use of computer technology (implementation of enterprise systems MRP/ERP), communication techniques (digital telephony, Internet, Intranet) and modern tools and applications that automate office work, engineering, manufacturing, services and administrative work play an important role. The use of IT in restructuring business processes companies does not, however, mean the automation and computerisation of existing processes, but the search for and development of new patterns, models and solutions. IT offers a wide spectrum of projects supporting restructuring, beginning with the implementation of standard software packages, and ending with the construction of systems dedicated to the needs of a business organisation.

On the basis of the above considerations, it is possible to formulate a working thesis that the implementation of enterprise systems MRP/ERP provides an efficient support for restructuring changes in the company and brings benefits in the functional and strategic areas.

In detail:

- *outcome of the functional area*: employees benefit from the automation of processes, e.g. one-shot input of source documents into the system and the possibility of obtaining rights of access to functions associated with a particular task;
- *benefits of the strategic area*: management has the ability to assess the current financial condition of the company monitoring the level of material resources and storage, rational planning of activities in the area of staff management, wage policies, improvement and development of human resources (HR), and intervention in case of irregularities.

The introduction of the implementation of supporting staff management project in the Municipal Transport Company (Miejskie Przedsiębiorstwo Komunikacyjne; MPK) and the analysis of technical–organisational–economic effects resulting from the IT project accomplishment are presented in the following sections of this work. On the basis of empirical studies, a close relationship between the completion of the various stages of project implementation and the restructuring of HR processes is demonstrated.

## 2.2 Organisation of the project

The development of information systems for personal processes is closely linked to the development of methods and techniques of HR management. In the 1990s, the functionality of personnel–payroll systems recorded the basic personal data of employees and payroll. Currently, this class of systems has been enhanced with modern features in the so-called strategic HR management supporting: modelling of the organisational structure, workforce planning, recruitment, management training and capacity building, as well as the assessment of labour and bonus schemes. It is worth noting that a change in approach to the management of HR in the business organisation was driven by several factors, namely, increase in labour costs in the enterprise, the impact of the HR function in the development of productivity and thus the impact on the competitiveness of the company and its market position, increase of employees creativity, and increase of the role of organisational culture in modern enterprises [6].

The use of IT in the computer-aided management of human capital is related to the increasing pressure to increase the efficiency, speed and cost reduction of the implementation of specific HR functions [2]. Computerisation may include some or all personnel functions. In particular, it may be applied to increase efficiency in the selected area or a wider one, building competitive advantage across the enterprise. For example, the recruitment and selection process increasingly involves the use of specialised applications and information systems category Applicant Tracking Systems (ATS).

The functionality of the ATS system includes publishing and export advertisements for print and online media; recruitment channel management and collection of information about the sources of origin of the candidates; advanced sorting and search listings, applications, and candidates; and even examination of the alignment degree of candidates to the designated criteria. The popularity of the recruitment process management systems in Poland is prevalent among big companies (over 250 employees), where every third employer uses this class of applications [11]. Applications of ATS can be an integral module of larger systems installed in the company covering many areas of its business that are often implemented by large companies.

On the other hand, smaller companies have the opportunities to take advantage of the solutions available in the Software as a Service model on a lease, usually at constant subscription payments. It is more advantageous financially and the responsibility for the maintenance and safety remains with the supplier.

Therefore, more and more enterprises introduce complex and multi-process supporting personnel management systems in place of simple applications supporting the records of employees and payroll. The popularity of these category solutions is also associated with the development of the domestic producers of integrated packages MRP/ERP, firms providing consulting, implementation and information services as well as Poland's integration with the European Union (EU) countries.

The domestic market for computer systems supporting staff management should be assessed both as mature and competitive. For the specific needs of the Polish market and national legislation, solutions offered by reputable manufacturers including software companies SAP, Oracle, or IFS were adopted. Systems supporting personal processes are also offered by domestic companies of the IT industry, which effectively compete with Western solutions. The leading domestic providers of systems integrators include TETA, COMARCH and SOFT-LAB.

Recommended for Municipal Transport Company (MTC) information system should certainly support the management processes at the functional and strategic levels. It should be noted that the implementation of advanced features includes: employees relationship management, forecasting and simulations of wage costs, job evaluation techniques, as well as linking staff development policy with the company's strategy that

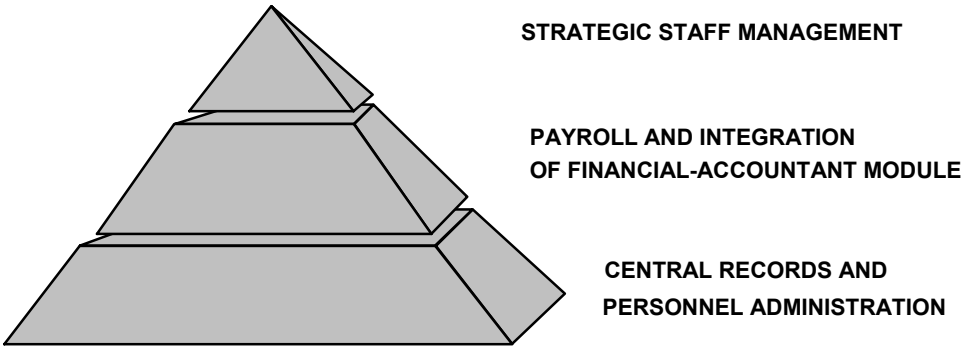


Figure 1. The implementation of system supporting human resources management: stages of work implementation (*source: own elaboration*)

requires a reorganisation of primary and secondary processes associated with HR and payroll records.

The project of implementation of the systems supporting HR (Fig. 1) in the Municipal Transport Company (MPO) is initiated by a functional analysis proceeding to three implementation stages:

Stage 0 – Functional analysis

Stage 1 – Implementation of the software functionality in the central records and personnel administration area

Stage 2 – Implementation of the software functionality in the payroll area including the integration of financial-accountant module

Step 3 – Implementation of the software functionality in the area of strategic HR management. The material effects of the realisation of specific implementation tasks and economic effects associated with the launch of the supporting system of staff management functionality will be discussed in detail in the following sections of this article.

### 2.3 Functional analysis

The purpose of functional analysis is a new circuit design of source documents, the specification of inputs and outputs, and a coherent approach to the restructuring of business processes (reorganisation of functions, processes and organisational structures) for the project system.

The primary carrier in the process of personal information is source documents. They form the basis of personnel records and from the legal standpoint are important players. The classification of personnel documents can be carried out according to various criteria.

Due to the place of issue, the personnel documents can be divided as follows [7]:

- Internal – made by different entities of the organisation; examples are contract of employment, job description, roles and responsibilities, recognition of improved qualifications, documents related to the granted prizes and awards, and application for leave,
- External – made by various entities of the company's environment; examples are previous employment certificates, skills for work certificate, periodic health examination, statutes and regulations.

According to the type of recipient, personnel documents can be divided as follows [7]:

- Internal – produced for different stakeholders of the organisation, i.e. structure of employment report, labour costs reports, work time and holiday settlement reports, and employee development certification,
- External – produced for various entities of the organisation's environment, i.e. Social Security documents, a report on the state of employment for the Central Statistical Office, and employment and earnings certificate for banks and other institutions.

The introduction of the implementation of supporting staff management project in the Municipal Transport Company (MTC) embraced a framework for the analysis of factual records and verification of all types of documents currently operating in the area of payroll, development of a new business process configuration, verification of wage components and algorithms for each professional MTC group, and the implementation of employee development and training concept.

More specifically, functional analysis included the following categories of work:

- registration and substantive verification of all types of documents existing in the area of payroll including:
  - analysis of the structure of source documents recorded in currently working MTC information systems (e.g. payroll software) and helper applications (e.g. MS Excel spreadsheet package used for storing personal data of employees),
  - analysis of the records and reports structure issued by the currently operated systems in the MTC, automated reports (e.g. through manual data consolidation in MS Excel spreadsheet) and hand written reports,
  - evolving document classification rules (e.g. classification into official documents and internal MTC documents) and assigning each document to separate earlier category:
    - development of a record of divergences – the list of redundant and missing documents/reports,
    - the structure and information content development of new documents/reports,
- development of a new configuration of business processes in the area of payroll including:
  - analysis of document flow system in the area of HR: payroll and analysis of information linkages with other organisational units of the company,
  - assessment of data redundancy, i.e. repeatedly entering the same data and information into various domain database systems,
  - project of the business processes new organisation in the area of payroll for the enforcement of computing system project,
- verification of components and algorithms wage for each MPK professional group including:
  - registration of salary components together with a description of the legal grounds or reference to the MTC internal regulations,
  - developing payroll algorithms for individual MPK company occupational groups,
- development of the implementation concept of staff training and development in the MPK system including:
  - development of the organisation planning principles: evidence principles of the organisational structure and the structure and job descriptions (competency requirements, rights and obligations),
  - development of staff recruitment rules: the rules of applications for the recruitment needs (unification and joint planning for the similar needs of different branches/depots), the criteria for staff recruitment (individual candidate competency profile) and the principles of candidate assessment,
  - development of employment eligibility and selection rules for each job: the principles of detailed description of the employee competence in relation to particular occupational groups in the MPK and the rules of periodic employee appraisals,
  - career path development planning: the principles of the development and upgrading workers' skills and the rules of defining career paths for individual employees (by succession according defined key positions and career levels).

According to the normative standards for project implementation, a report of the analytical works has been submitted for approval to the Steering Committee that acted as the so-called Project Supervisory Board. Upon acceptance of this document, proper implementation works related to configuration, parameterisation and training for future users have been carried out. On the other hand, after the completion of the implementation, the individual modules of the system have been put in operation.

### 2.4 Implementation of the functionality in the central records and personnel administration

The first stage of implementation is launching a centralised system of personnel records (personal data, competences and rights of the employee, permanent payroll information) and personnel records system (recruitment, dismissal, records of absence, sick leave, holidays, etc.). The material effect of the first stage is produced by homogeneous information system (based on a central database) supporting HR management at the operational level (access to current information on the employee and his archival data) and at the strategic level (automated generation of reports and statistics on selected occupational groups). Access to the various categories of personal data has been carried out in accordance with a scheme of roles and permissions. Obligatorily, the new system meets the requirements of the *Data Protection Act*. Bearing in mind a barely

existent central personal database and personnel records system at the Municipal Transport Company (*MPO*), tangible benefits at both the operational and strategic levels have been achieved.

- Operational level

Organisation and centralisation of information resources, eliminating data redundancy, i.e. repeatedly entering the same data into domain systems, the ability to access employee data from any corporate terminal network saving the log-in and access authorisation procedures. Registration of employee personal data and other required information (qualifications, periodic health examination, training and courses, etc.).

Implementing standard operating procedures and information systems to ensure that processing and archiving of personnel data are secure. Hitherto, dispersion, disintegration and outdated technology of the existing Municipal Transport Company (*MPO*) applications that stored personal data did not guarantee the minimum security paradigms. For example, the use of MS Office software to build personal records does not allow the implementation of the basic mechanisms of authorisation and access control to information. What is more, the lack of elementary file security creates a real opportunity for stealing personnel data or execution of illegal copies. Another example is the manual transfer of payroll drivers' data to the "Payer" program. This transfer involves manually copying the payroll drivers' data for the current accounting period. These data are copied from the local servers of branch offices (Municipal Transport Company depots) and then manually merged and loaded into the "Payer". This process does not meet the minimum security requirements and also generates high costs associated with control of the accuracy of data transfer (two employees were assigned to it). It is obvious that the introduction of an information central system will eliminate the identified anomaly, ensure security of personal data and significantly reduce processing costs.

- Strategic level

Acquisition: timely and accurate reports on personal resources. Up to now, the preparation of a simple report on the structure of staff employment in the Municipal Transport Company (*MPO*) referring to seniority and rates broken down by occupational groups required manually copying, merging and formatting data of a number of distributed applications. These applications stored only fragmentary portions of the data. Due to the variety of data formats, the lack of a standardised identification of employees and dispersion of information, the process was time-consuming (on the average, two or three person-days). The quality and reliability of the hand written statements and reports (manually copying and merging of data can generate numerous errors) are also arguable. In practice, the disintegration of the data and application prevents the formation of multi statements and reports as well as advanced forecasting and simulations on the structure of employment and payroll. It should be noted that an integral element of the so-called "high-end" modern information systems is called report generator. This tool allows modification of the existing and construction of new combinations, reports and statistics, and graphical visualisation of statistical data using various types of graphs. Access to individual reports should be strictly related to the implemented mechanisms for authentication, roles and permissions.

### 2.5 Implementation of the functionality in the area of payroll including the integration of financial-accountant module

The first stage of works (construction of the Municipal Transport Company standardised staff system) will centralise payroll (second stage) and automatic (error-free) data transfer to the financial-accounting system and the "Payer." Calculating payroll (Fig. 2) is a relatively simple process that comprises a sequence of successive operations:

- definition of payroll includes the following: payroll ID number, the taxable and accounting period,
- download data from the source (employees and payroll components): based on a payroll template, previous payroll or manually entered data,
- payroll configuration: download of parameters in force at the payroll date (based on the fixed documents and closed flow documents),
- conversion of downloaded components and checking of calculations,
- automated export and payroll accounting (financial accounting module): on the basis of pre-prepared accounting principles.

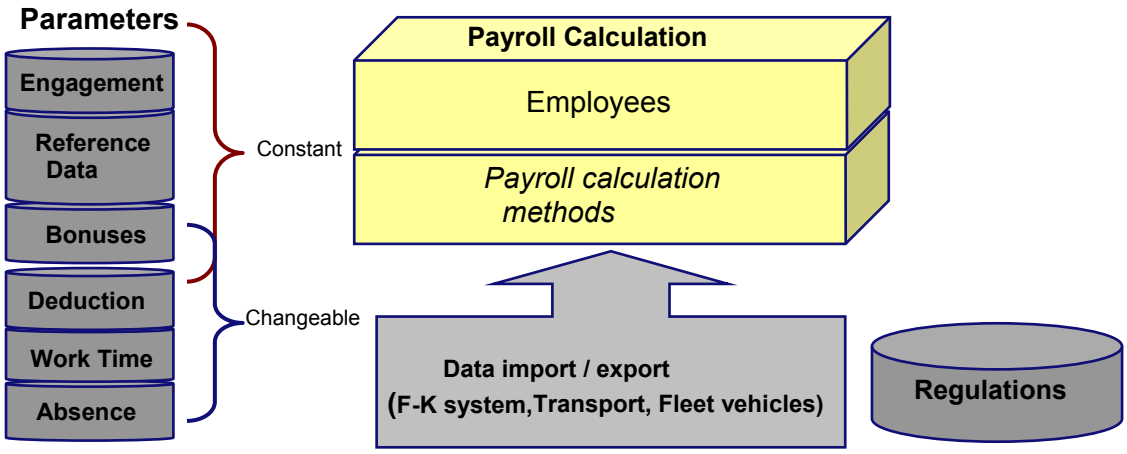


Figure 2. Module functional architecture supporting calculating payroll (*source: own elaboration*)

The Municipal Transport Company enterprise payroll system should guarantee the settlement of wages for different occupational groups. In short, the first group settlements are the workers employed in the position of white collar workers, then the drivers and blue-collar workers (staff, facilities and contract workers). The introduction of a central payroll system will eliminate the disintegration of existing applications that enables fully automatic (error-free) data transfer to the financial accounting system and the "Payer" program. Introduction of the enterprise system will provide real savings that result from the centralisation of organisational structures in the process of payroll (operational level), and also enable the rational implementation of remuneration policies (strategic level).

### 2.6 Implementation of the functionality in the area of strategic staff management

The launching of financial accounting system (i.e. the end of stage I and stage II) is the basis for the development and implementation of the so-called Municipal Transport Company (MPO) personnel policy, as well as adequate solutions to support the strategic management of HR. In the implementation of the so-called "soft elements of HR", the flexibility of the implemented system is extremely important, i.e. the possibility of customisation and adaptation to the specific needs of the enterprise as well as the qualifications and experience of the company that accomplishes the implementation project.

- Flexibility and customisation of the software

IT solution should support the development of personnel policies in accordance with the mission and strategy of the company. More specifically, in the process of implementation the appropriate software components are flexibly selected, combined and configured. For example, in modules such as managerial portal and strategic scorecard, great emphasis is also put on the appropriate configuration of visual elements. In the process of implementation configured elements affect: ergonomics and the information content of the dialog boxes (or websites), categorisation and filtering of data (a set of panels, drop-down lists and selection screens) as well as the visualisation of data using summaries, diagrams and charts.

- Knowledge and experience of the team of consultants on the side of the company that is implementing the implementation project

Traditionally, based on many years of experience, a team of consultants has many scenarios, models and preconfigured solutions that greatly accelerate the process of developing organisational computer solutions for the next customer.

At the operational level, the most important benefits of the introduction of new organisational and information solutions may include: computer aided recruitment process, the implementation of the electronic training system and employee portal. On the other hand, at the strategic level, the implementation of tools supporting the analysis of staff needs as well as verification and evaluation of personnel is particularly important.

- Operational level
  - Computer aided recruitment process. On the basis of the automated comparison of information on the required recruitment qualifications

and candidate skills database, it is possible to obtain a ranking list of candidates. Organisational and economic benefits: a high degree of accuracy with candidate selection for a specific position, reduction of operating costs.

- Direct employee access to personal information via terminals and Intranet (within its powers) and the submission of some documents (such as leave requests) in electronic form. Organisational and economic benefits: accelerating quality improvement in information access, and reduction of personnel costs related to employee service in the branches.
- Planning and organising effective personnel training (applying e-learning software). Organisational and economic benefits: improvement in teaching effectiveness and cost reduction (research conducted by Garthner Group shows that electronic training are about 40% cheaper than traditional forms).

- Strategic level
  - Analysis of staffing needs. Having information about the skill set (employees) and required (position, etc.) qualifications, it is possible to analyse training and staffing needs, check the use of staffing potential, create a career path, study the effects of changes in staffing, keep internal and external recruitment, draw up ranking lists, and create job descriptions.
  - Employee assessment performance. Implementation of the periodic appraisal system; comparative analysis of the so-called current review of personnel ratings with archival data.

In summary, the modern systems supporting staff management offer predefined solutions in the area of building the company organisational structure, handling the recruitment, training, competency management and development strategy of the availed HR. The last phase of the project was the implementation of functionality in the so-called area of strategic HR management.

## 3 IT and integration aspects of the project

System supporting staff management should be characterised by the so-called openness, i.e. the possibility of data exchange and integration with other Municipal Transport Company (MPO) systems, in particular, with financial accounting package and "Transport" system (Fig. 3).

In practice, there are quite often solutions found where personnel system is integrated with external (separate) financial software. Batch processing is used in data transmission, in subsequent accounting periods. Thus, in the course of the project, content and format of the so-called swap file must be determined.

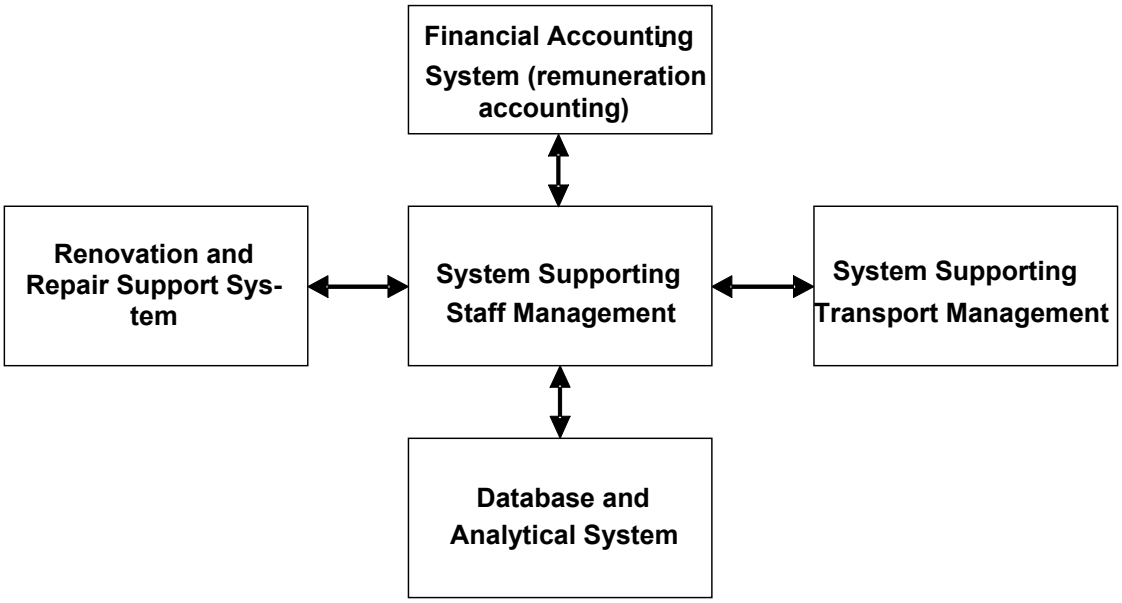


Figure 3. Integration of supporting staff management system with other information systems (*source: own elaboration*)

The computerisation of the transport process includes the planning of work time drivers (including leaves, holidays and sick leaves) and the disposition that requires the development of integration solutions between the support staff management system and "Transport" system.

The planned division of tasks between system supporting the functioning of the transport process and modules of personnel-payroll package requires an elaboration of the infrastructure integration project and the methods and frequency of data exchange. The number of objects and their attributes to be exchanged between different subsystems, agreed data formats and synchronisation method should be taken into account in designing integration solutions.

## 4 Summary

European initiatives addressing the problem of the EU's competitiveness on a global scale increasingly emphasise the key role of information and communication technology in the transformation of the EU towards a knowledge-based society. In accordance with the priorities of the "Europe 2020 Strategy", an effective use of computer technology (implementation of integrated systems MRP/ERP), communication techniques (digital telephony, Internet, Intranet) and knowledge management tools, among others, Business Intelligence, OLAP and Data Mining (cf. [1, 3, 9]) will play an important role in the development of Polish companies.

Comprehensive computerisation is, therefore, an integral part of strategy to strengthen the competitive potential of the company, as well as the implementation of the restructuring changes. The purpose of this process is continuous reduction of operating costs and provision of support to the new innovative forms of economic activity.

A rational management of personnel resources was implemented in the analysed communication company. A system of central staff registration and a package of tools to support the analysis and monitoring of personnel resources were also introduced. A standardised remuneration accounting system was implemented and process for handling payroll obligations was modernised. Completion of particular work and implementation tasks were associated with the restructuring personnel process. An integral part of the process of HR and payroll centralisation had an effect on the new organisation of work, development of a new document flow and tasks and responsibilities distribution. However, the organisational changes of the realisation of specific implementation tasks should be introduced gradually that justify the division into three project phases.

Domestic passenger transport market is mature and competitive. Local authorities and local government institutions are responsible for the smooth functioning of municipal transport and operators of particular communication routes and lines. The selection process of company passenger services takes place in a non-limited tender according to the Public Procurement Law rules and regulations. Customarily, the primary criterion in tender proceedings is the unit price for the so-called vehicle kilometre. On this basis, the offer price of operating on individual routes and lines is calculated.

The elements of cost in the investigated company include over 58% of direct labour costs incurred in the form of remuneration paid to the drivers, staff facilities and white collar workers (the remaining costs are identified with 18% of fuel, 16% of service and maintenance of fleet vehicles, 8% of outsourcing and fiscal charges). Centralisation and integration procedures in the personnel area allowed the current staff needs analysis, verification and selection of staff and effective wage fund management. The economic effect of the process of comprehensive computerisation of the personnel process are the following: reduction of operating costs associated with personnel–payroll service, savings resulting from the introduction of a standardised wage policy, and more importantly the possibility of forecasting and simulation of salary costs based on analysis of historical data and analysis of employee future liabilities arising from wage policy and wage indexation.

As already mentioned, the implementation of information system supporting the personnel process was to improve not only the staff–payroll processes but above all management processes concerning strategic planning of the employment and wage policies shaping the future. Employees' remuneration is a key component of the company operating costs and, thus, the analysis of current and projected payment rates is undoubtedly the basis for a reliable calculation of the offer price for the provision of services in future tendering. The synergistic effect takes place here. Restructuring and computerisation of the personnel pro-

cess have a direct impact on the Municipal Transport Company (MTP) strategy to gain a competitive advantage in the passenger transport market where the price service is the basis for the contract calculated as the price per vehicle kilometre.

The tangible result of the implementation of the integrated system is, therefore, not only streamlining and computerisation of primary and secondary processes, but mainly to support decision-making and management processes. Unfortunately, several times the scope of the project implementation is limited to run functions in support of the operational area that in practice is seen as a simple replacement of the software. Research carried out in the MTP showed that the launch of the functionality to support management processes, i.e. *controlling* of wages in conjunction with the rational planning of employment, results in long-term savings while increasing the competitiveness of the company.

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# USEFULNESS OF SOFTWARE VALUATION METHODS AT INITIAL STAGES OF ERP IMPLEMENTATION

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***Abstract:*** This work discusses the problem of selecting methods for valuing the costs and estimating the time of implementing computer systems in cases when system modification is necessary. The methods presented in literature are reviewed and the stages of strategic phase of implementation characterised. On the basis of the analysis of data required by each method and the data obtained at different stages, appropriate selection of methods for each stage was proposed.

***Keywords:*** ERP, IT project, COCOMO, Delphi method, function points, implementations.

## 1 Introduction

The first ERP-class information systems (IS) were available in large companies only [1]. High implementation and maintenance costs were a barrier for their proliferation. With the decrease of costs, the group of users also covered medium and small companies. The first systems were tailor-made for individual customers. Their functions suited the organisations they were made for but their production costs were excessively high. Gaining experience from work with different clients, the producers selected a set of functions that reappeared in most versions and offered it as a standard version of their product. At the moment, all significant producers have their standard product: SAP, Business Suite; Microsoft, Dynamix AX; JD Edwards, EntrepriseOne; and so on.

During trade talks while selling standard ERP systems, the parties (suppliers and clients) reach a conclusion that the organisation of processes in the company does not fully overlap with the processes supported by the computer system that is available [2]. There are a group of processes that are not represented in any functionality in standard ERP system. This generates a need for adapting IS to a company. The costs of modifications increase the value of the contract (implementation). In some cases, it is the company that adapts processes to the system; however, the costs of organisational changes are an additional burden to the client. It is only when clients recognise the costs of system implementation (including adaptations) that they incline to consider changes in their organisations. In such cases, either the value of contract will be higher and the system will overlap with the processes in the company or the value of contract (costs for the client) will be lower and the client will need to adapt the organisation to the IS to a certain extent. For this reason, cost estimation at very early stages of implementation is crucial for system suppliers. Employing appropriate methods at each stage will allow the suppliers make earlier and more precise estimations of costs. As a result, they will generate lower costs of concluding a contract and increase the chances for a successful implementation of the project.

The aforementioned adaptations of IS to the company are the modifications that involve redefinition or broadening processes or structures of data implemented in IS. Standard sets of functionalities are similar for all software providers. The differences concern additional functionalities for different businesses. For instance, margin analysis in construction industry may be based on projects (revenue and project costs), whereas in metal production it can be defined on the basis of assortment groups (income from selling articles from a given group and production costs). It is important to define standard functionalities, as they will be the object of modifications [3]. These changes do not concern any other than ERP-class systems. Single-activity IS (e.g. sales with limited and closed functionality) do not need to be modified. Prospective clients (small companies) select readily available software by analysing correspondence with the processes in their company.

The methods facilitating valuation of software production are known and discussed in literature, e.g. by McConell [4]. However, due to changes in information technologies, the popularity of their use also

changes. The use of algorithmic methods at initial stages of information projects is difficult.

At this stage, there are no analytic or project documentations whose components facilitate estimating algorithms. Despite the fact that the uses of algorithmic methods at early stages of information projects can be found in literature [5, 6] the practice of information project suppliers indicates a common use of non-algorithmic methods as faster (i.e. cheaper) and easier. One can find suggestions for using cost evaluation methods for information projects, starting with statements that any combinations of methods should be used, through views about when and what methods should be used, and finishing with "step by step" procedures [7]. There are however, no guidelines advising a given method depending on the stage of implementation.

Negotiations with ERP system suppliers and clients concern implementation costs and time. For estimating the cost of software, one may use such time-consumption measures as man hours, man days or man months. With a given cost of a working unit of time for implementation, it is possible to calculate the cost in a given currency and the time (dates) of implementation, with consideration for possible simultaneousness of works.

What is known are the stages of software lifecycle [8] and software valuation methods [4]. The range of the problem was limited to ERP-class IS. The question is which of the evaluation methods produces most appropriate results of costs and time at a given stage of project implementation. The limitation is in the quality of necessary input data at given stages.

Section 2 of this article includes the description of stages in the strategic phase of implementation project with consideration for the data available for valuation. Section 3 is a review of algorithmic valuation methods. Section 4 includes the description of non-algorithmic methods. The final section presents the conclusions resulting from the connection of effects from lifecycle stage and the data necessary for software valuation. This is how alternative uses of methods at each stage are proposed.

The use of symbols in Figures 1, 3, 4 and 6 is in accordance with BPMN 2.0[1], even if full schemes may not be coherent with the notation [9].

[1] BPMN (Business Process Model and Notation) – a graphic notation for describing business processes.

## 2 Lifecycles stages of ERP system implementation

Numerous authors describe software lifecycles focusing on software production or writing software on an individual client's order [8, 10]. None of the presented models corresponds entirely to implementation process of ERP-class software in a middle-sized company. They do not consider "movability" of the end of strategic phase (concluding a contract) and possibilities of having one additional stage – feasibility study. Feasibility study is not significant for software lifecycle; however, it provides information for project valuation.

The stages of IS implementation may be categorised as follows:

1. initial trade talks,
2. pre-implementation analysis,

2'. feasibility study,

3. system change project,
4. implementation of changes and testing,
5. test installation and initial import of historic data,
6. system validation,
7. training,
8. final installation and proper data import,
9. user assistance,
10. in-use changes.

The grouping of the stages in phases is presented in Figure 1.

Considering cost evaluation, one should remember that in the sales process, the moment of contract conclusion is significant. Up to this moment, the supplier estimates the costs, while later they verify and predict the costs hoping that they will not exceed the income. Contract conclusion may happen right after stage 1 but not later than stage 4. This period is called the strategic phase. It is in IS supplier's interest to get the contract signed as soon as possible, as the implementation of subsequent stages increases the costs with the risk of failure of concluding the agreement. However, early estimation of costs involves higher risk of estimation error. A convenient situation, from the supplier's point of view, in which the client agrees to sign an agreement for implementation analysis is very rare. It is only after its completion (and valuation) that the parties sign an implementation agreement for other stages. For this reason, stages 1–3 are important and these are the ones that are going to be discussed in subsequent sections of the present work.

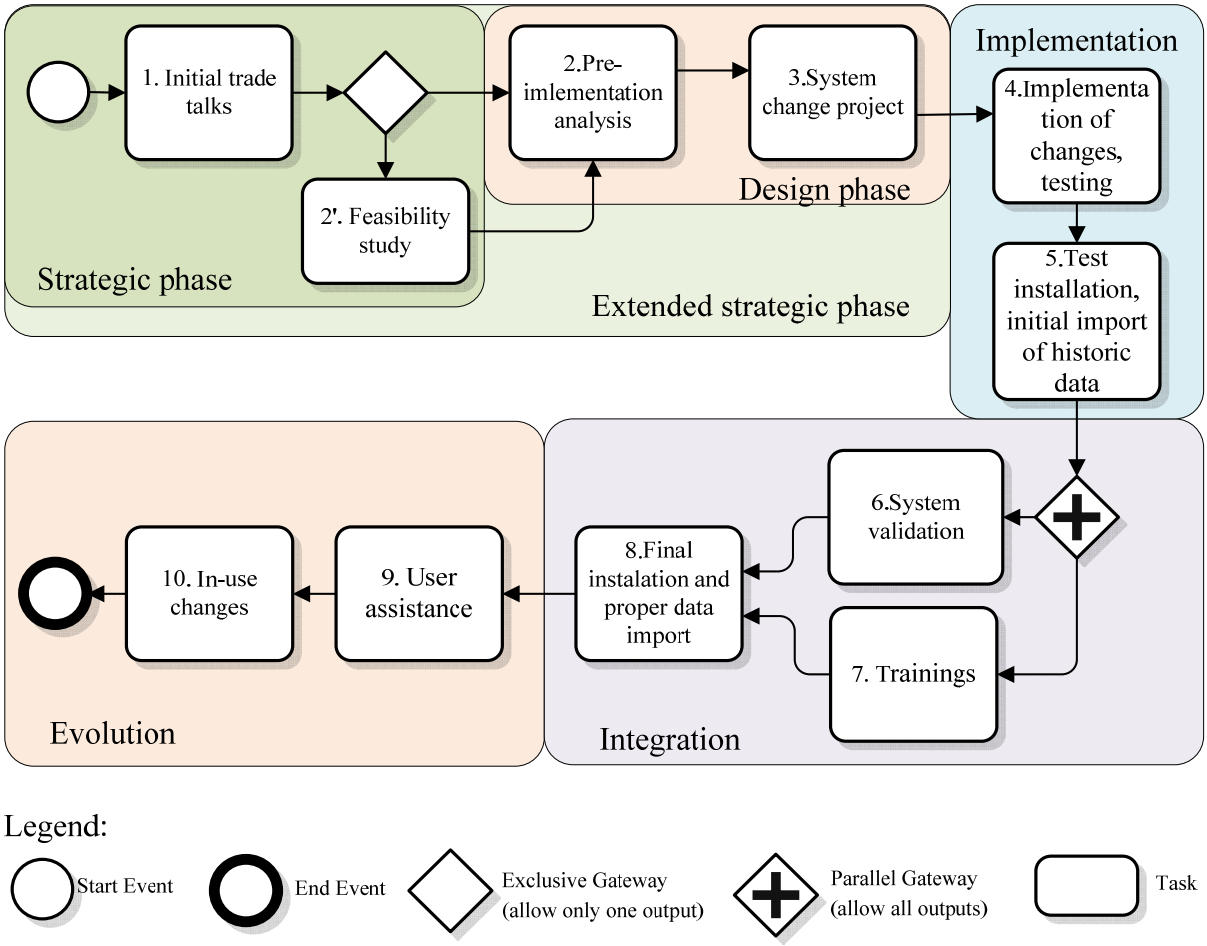


Figure 1. ERP-class information system lifecycle implemented in a company

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### 2.1 Initial trade talks

The supplier has meetings with a prospective client in order to define the range and value of the contract. Usually, it is conducted in one or two initial meetings followed by two or three presentation meetings. Some of the elements of work range are identified quickly and precisely. These concern primarily the computer hardware, network infrastructure and licences for individual ERP modules. Some elements, e.g. IS modifications that result from non-typical users' requirements are difficult to define.

At this stage, the supplier cannot fully identify the needs that are not satisfied by the standard version of ERP system. As clients' knowledge on IS comes from trade presentations, they cannot define precisely which requirements are not standard. As an example, the general range of contract is presented below:

A. hardware – supply: 12 computer work stations, 1 server in accordance with the specification

B. information infrastructure – service: 25 electric and logical access points and two WLAN access points in client's office building

C. licences: financial module – 4 users; personnel module – 3 users; logistics module – 12 users: sales module – 4 users; production module – 11 users

D. adapting IS in for logistics and production processes

E. training: 30 man days (3 days on financial area, 6 days on personnel, 12 days on logistic, 4 days on sales, 5 days on production)

F. assistance for users at work: 25 man days.

Except for part D, the supplier has sufficient information to present a price offer to the client. Moreover, using the description of the range in such a form as e.g. in part E or F, they secure against the client's changes in requirements for this range. If it happens in the course of implementation that the client will need 45, rather than 25 hours of assistance, and the amount in the contract stipulated at 25 hours, the supplier will have the right to additional pay.

The situation is different with IS modifications from part D in the above range of contract. At this stage, the supplier holds a set of client's general and specific requirements. The reason for non-uniformity of specificity of the requirements (general and specific) is the client's lack of experience and knowledge. Specific requirements are encountered sporadically and are most frequently related to presentation of data in the system (prints, listings, etc). One should remember that the aim of this stage is not collecting the requirements but concluding a contract. The requirements are obtained, as if "by chance", from presentations and talks with the client. Thus, the supplier is aware that there is still a subset of undisclosed requirements.

The supplier who decides to evaluate IS adaptation must consider the above "faults", including undisclosed requirements. Estimation error and the risk of underestimation are usually high.

### 2.2 Feasibility study and pre-implementation analysis

If the supplier was unable to evaluate system adaptation (modifications), works aimed at clarifying and specifying client's needs must be conducted. Then, a pre-implementation analysis or feasibility study is done [11]. Although both solutions are aimed at specifying the data for the evaluation, the basic purpose of each is different. If the supplier estimates the chances for signing a contract as high, they order a feasibility study. The work is less expensive and in case of concluding the contract, some effects may be used in pre-implementation analysis.

Feasibility study includes information on the company in a form of a systematic document based on economic facts [12]. The information concerns economic, organisational and technical aspects [13]. The aim of the study is to define the range of works (including modifications) and the costs of the project. The document is used by supplier's decision-makers while analyzing economic aspects of project implementation.

Pre-implementation analysis includes exclusively the information concerning the computer system in the context of a given company. The result is a report including the following components: functional range of the implementation, list and description of business processes, functions and data advised to be included in the functional range of the system, organisational range of the implementation, proposed aims of the implementation, expected business benefits, and schedule of work [14]. For example, two requirements may appear as in the following:

- L.03.12.02 – invoice for clients from outside EU should include an amount to pay in the client's currency with the number of Polish National Bank currency exchange table that was used to calculate the amount in the field "comments",
- L.03.12.05 – operator issuing VAT invoice should be able to print the document, save it as PDF file or e-mail as an attachment in PDF file to the address from "e-mail" field in client's database.

The numbering of requirements from the example is in accordance with WBS[2] [15] and may mean: L – logistics, 03 – group of requirements concerning sales processes, 12 – subgroup of sales invoices and 02 – the number of subsequent requirement in subgroup 12.

Even in a medium-sized production company, the recording all user requirements would be very time-consuming and expensive (from a few up to over a thousand requirements). Moreover, in most cases, they would overlap with the records in ERP system documentation. Therefore, suppliers make a differential analysis that includes only those elements that are not covered in a standard IS. Such a procedure shortens the time of stage implementation but also allows the client to see the documentation of a standard version with the pre-implementation analysis in order to get an idea of the future system.

At this stage, the supplier assumes that the requirements are complete and the level of their specificity meets the deed of the designers to whom the document is addressed. At the same time, the documentation of implementation analysis (specification of requirements) is going to be used for labour valuation.

### 2.3 Project of system changes

Project of IS is an intermediate phase between defining the requirements and the implementation. The documentation that is produced is indented exclusively for internal use of the supplier (software departments).

[2] WBS (Work Breakdown Structure) – a basic technique in managing projects that allows defining and organising the range of project with a hierarchic tree-structure.

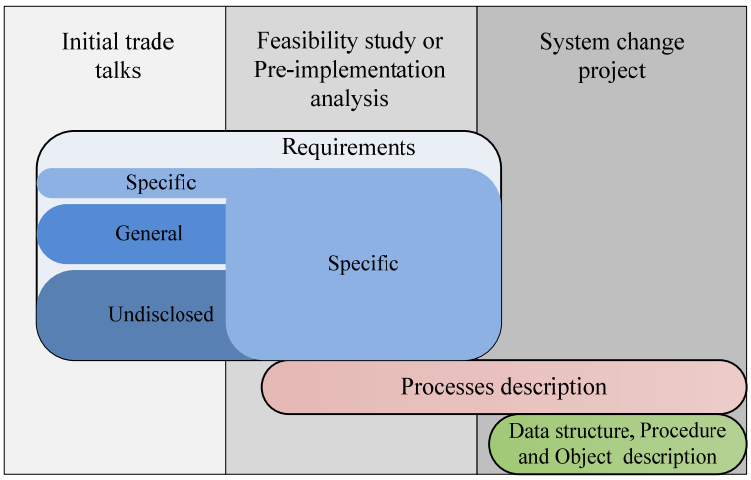


Figure 2. Input information necessary for valuation at initial stages of lifecycle.

Depending on the methods of implementation (structured, object-oriented programming, agile software development, etc), project documents may include different elements [8]. Some ERP system developers worked out their own specific methodologies. In such cases, the documentation will be specific. One such example is Select Perspective methodology[3] [16, 17] or ARIS[4] [18]. However, there are always common elements for evaluating software.

The first element of software developing is to specify the requirements resulting from implementation character. The level of requirement specificity must determine the manner of implementation in an unambiguous way. Despite this, project documents include the elements describing data structures and procedures of processes. There are a number of methods for presenting project information: from DFD, Entity-Relationship Diagrams [19], through Unified Modelling Language (UML) models [20]. Each of them is an appropriate source of data for software evaluation.

### 2.4 Summary of lifecycle stages

With subsequent stages of software lifecycle, the supplier's knowledge of the client's organisation enlarges. In the first two stages, only requirements are obtained and after the project stage such elements as data objects (tables, fields) and interface windows are also known. At the same time, the supplier's costs will be rising. If a contract with client is concluded, the costs will be included in the contract value; if not, they will be the supplier's cost. Input information necessary for making valuation at the first three stages of project lifecycle is presented in Figure 2.

## 3 Algorithmic methods of software evaluation

### 3.1 COCOMO II method

Constructive cost model (COCOMO) method was proposed by Barry Boehm in 1981 [22]. Since then, a number of versions and types of this method have been developed, e.g. COCOMO81 and COCOMO II [22]. It is used to calculate Person per Month (PM) on the basis of Kilo Source Line of Code (KSLOC) (process 1 in Figure 3). KSLOC calculation is done on the basis of project components. Because for many contemporary uses, the use of source lines does not correspond with PM, the method was modified by using function point (FP) analysis, as presented in section 3.2 [23] (process 2 in Figure 3). The complete sequence of process realising COCOMO method is presented in Figure 3.

The first activity is defining five scale factors (SFs) (process 3 in Figure 3), whose value is determined empirically in five classes, depending on the level of complexity (from very low to very high), which is presented in Table 1.

[3] Select Perspective – formalised by Select Business Solutions Inc, a set of best practices supporting software development and its controlling.

[4] ARIS (Architecture of Integrated Information Systems) – a method of analysing and modelling industrial processes that lead to building an integrated system of information processing.

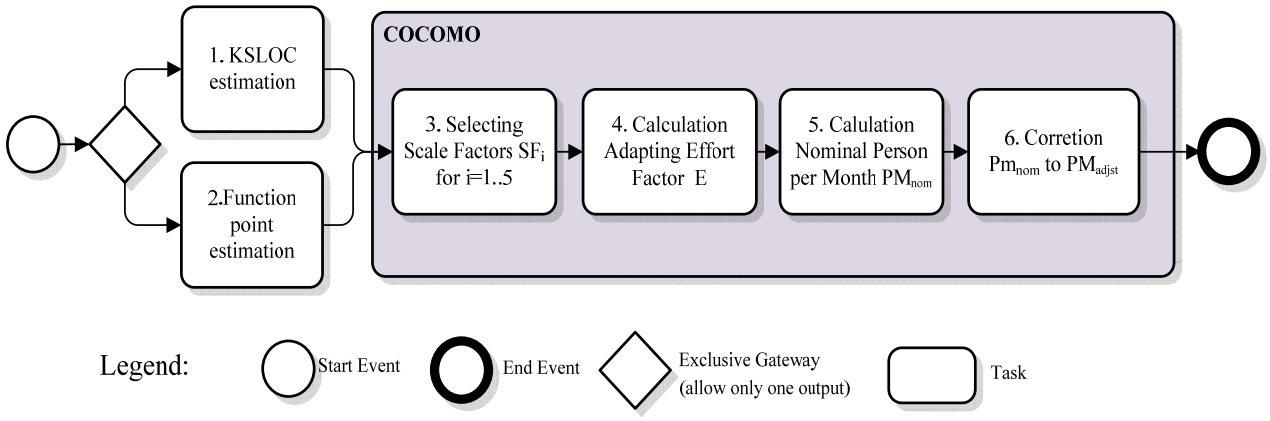


Figure 3. Sequence of processes in constructive cost model method

Table 1. The value of scale index [23]

| i | Scale factor | Very low | Low | Normal | High | Very high | Extra high |
|---|---|---|---|---|---|---|---|
| 1 | typicality | 6.20 | 4.96 | 3.72 | 2.48 | 1.24 | 0.00 |
| 2 | flexibility | 5.07 | 4.05 | 3.04 | 2.03 | 1.01 | 0.00 |
| 3 | risk management | 7.07 | 5.65 | 4.24 | 2.83 | 1.41 | 0.00 |
| 4 | team maturity | 5.48 | 4.38 | 3.29 | 2.19 | 1.10 | 0.00 |
| 5 | process maturity | 7.8 | 6.24 | 4.68 | 3.12 | 1.56 | 0.00 |

Knowing the SFs, one may determine the indicator adapting effort E in accordance with formula (1):

$$\mathrm{E} = \mathrm{B} + 0{,}01 \cdot \sum_{i=0}^{5} \mathrm{SF_i} \tag{1}$$

where:

B – a constant 0.91 for COCOMO II model [23].

For instance, for the project in which typicality is low, flexibility must be high, risk management is very low and team maturity is normal and process maturity, the adapting factor, will equal:

$$\mathrm{E} = 0{,}91 + 0{,}01 \cdot (4{,}96 + 2{,}03 + 7{,}06 + 3{,}29 + 3{,}12) = 1{,}1146$$

Then, $\mathrm{PM_{nom}}$ nominal PM is calculated in accordance with formula (2) (process 5 in Figure 3):

$$\mathrm{PM_{nom}} = \mathrm{A} \cdot (\mathrm{Size})^{\mathrm{E}} \tag{2}$$

where:

Size – the number of code lines in KSLOC unit

A – a constant determined on the basis of previous projects = 2.94 [23].

Following the previous example, it is possible to calculate nominal implementation time for 8 KSLOC which equals ~ 30 man months.

$$\mathrm{PM_{nom}} = 2{,}94 \cdot 8^{1{,}1146} = 29{,}85 \approx 30 \text{ osobomiesiące}$$

For models from the first stages of Application Composition Model, Early Design Model [23] nominal time should be corrected (process 6 in Figure 3) in accordance with formula (3).

$$PM_{adjs} = \mathrm{PM_{nom}} \cdot \prod_{i=1}^{7} \mathrm{EM_i} \tag{3}$$

where:

$\mathrm{EM_i}$ – effort multiplier.

For the models in another lifecycle stage, Post-Architecture Model (when system project is known), the formula for nominal PM was enriched by indicators. They define $\mathrm{PM_{nom}}$ changes, depending on system reliability, database size, product complexity, recycling level, analysts' and developers' skills, and so on. Similar to SF values, EM was determined empirically. The complete list can be found in method documentation [23]. The literature includes a number of examples of adapting COCOMO method [24, 25] with the use of fuzzy logic, inter alia [26–28].

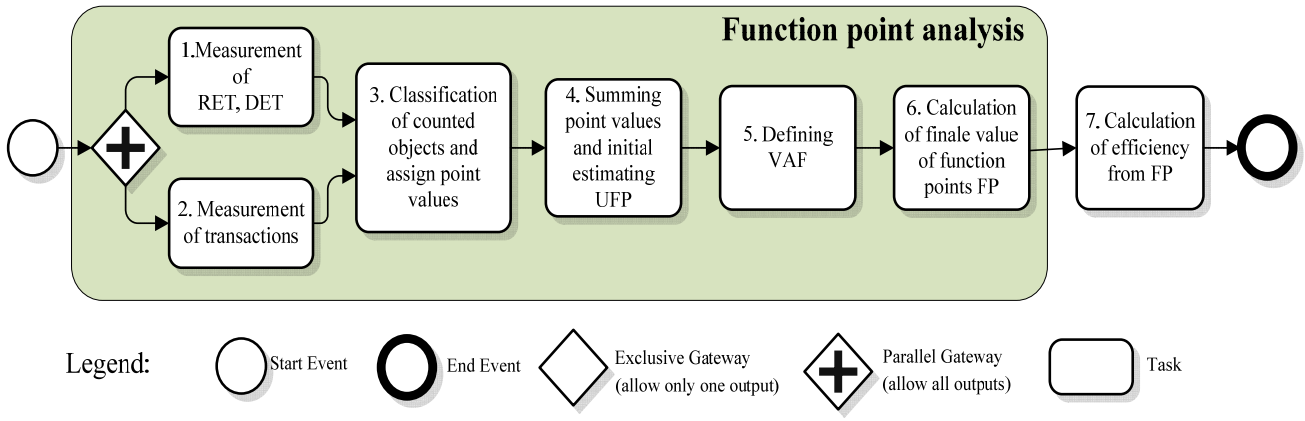


Figure 4. Evaluation process with the use of function points (FPs)

In practice [29], the COCOMO method is not used often. The reason for this is the need to use the size of code, which is known only at the stage of project documentation. Moreover, in project implementation, it is more frequent that the existing code is modified, rather than written from scratch. In case of code changes, COCOMO does not produce correct estimations. However, if the supplier uses FPs, evaluation can be started earlier – at the stage of implementation analysis. On the other hand, knowing the number of FPs inclines towards using evaluation by analogy method (presented in section 4.5), rather than COCOMO. This is because the supplier operates in known developer environment, in similar conditions and it is easier to determine multiplication factor and use it for every evaluation, rather than to do calculation according to COCOMO method each time.

### 3.2 FP analysis

The evaluation method proposed by A. Albrecht [30] requires the calculation of the number of FPs on the basis of specific requirements. FPs are a conventional measure complexity of function offered by the program. The number of FPs depends on the number of distinguished objects (reports, interfaces, etc), with the possibility of objects from one class (e.g. enquiries to database) having different values due to the level of complexity. For example, the value of FPs of a report referring to one table and two fields will be lower than the report referring to ten tables and eight fields. In the subsequent stage, COCOMO method, presented in section 3.1 or *evaluation by analogy* presented in section 4.5 can be used to calculate PM or costs. *FP analysis* is used to only to estimate software complexity or costs and its effects are not used at next stages of implementation (e.g. in the project). The method may be used for:

- software development,
- software modification,
- finished software product.

The evaluation process with the use of FP analysis is presented in Figure 4.

The FPs method is based on selecting five classes of objects in requirements or the ready program.

1) Internal Logic File (ILF) – a set of objects defining internal system data, e.g. a table in relational database,
2) External Interface File (EIF) – a set of objects exchanging data between IS e.g. an interface allowing data import from internet application,
3) External Inputs (EI) – responsible for inputting the data from the outside, e.g. screens, dialogues with the user,
4) External Outputs (EO) – responsible for outputting the data outside from the inside, e.g. prints, files send outside,
5) External Inquires (EI) – processes transferring internal data without modifying them, e.g. SELECT inquiry in Structured Query Language (SQL)[5].

Relations between classes of objects in the context of the environment are presented in Figure 5.

[5]SQL (Structured Query Language) – a structural language of enquiries used to build and modify databases and import or export data to and from the database.

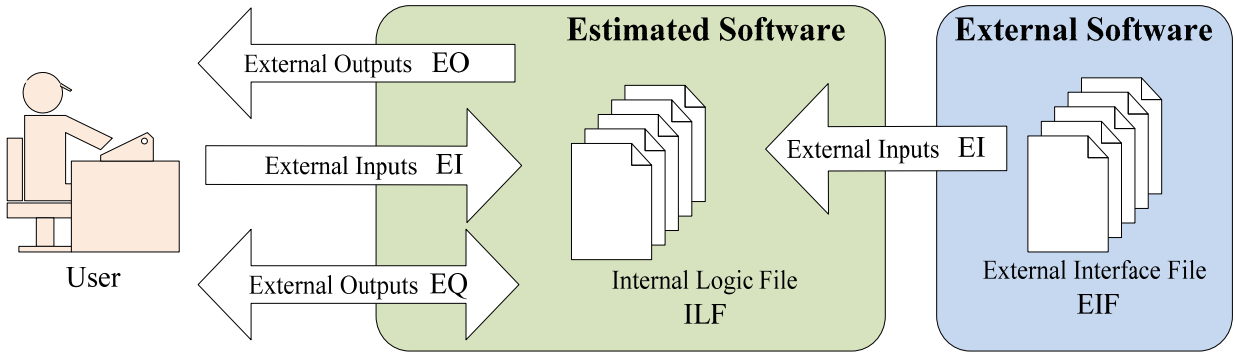


Figure 5. Classes of objects in function point analysis

The first two classes are related to data, and the other three to transactions. To make estimations in the first stage, the following indicators are used:

- RET (Record Element Type) – a unique, recognisable subgroup of elements given in ILF or EIF, which correspond to the record in the table;
- DET (Data Element Type) – a unique, identifiable field in ILF or EIF, which corresponds to the field in record;
- FTR (File Type Referenced) – recognisable by users, logically related data, which corresponds to files or relationally connected files.

All objects in classes must be identified and attributed with appropriate value of indicators (process 3 in Figure 4). ILF and EIF are described with RET and DET, while EO, EI and EQ with FTR and DET. For example: ILF #1: RET=3, DET=15. In this way, the values of unadjusted FP of a given object are read from table of weights (Table 2). For example, the aforementioned ILF #1 will have a value of 10 UFP.

Table 2. Weights of object classes, depending on DET and RET or FTR

| **ILF** | **DET ∈<1;19>** | **DET ∈<20;50>** | **DET > 50** |
|---|---|---|---|
| RET=1 | 7 | 7 | 10 |
| RET ∈<2;5> | 7 | 10 | 15 |
| RET > 5 | 10 | 15 | 15 |
| **EIF** | **DET ∈<1;19>** | **DET ∈<20;50>** | **DET > 50** |
| RET=1 | 5 | 5 | 7 |
| RET ∈<2;5> | 5 | 7 | 10 |
| RET > 5 | 7 | 10 | 10 |
| **EI** | **DET ∈<1;4>** | **DET ∈<5;14>** | **DET > 15** |
| FTR < 2 | 3 | 3 | 4 |
| FTR 2 | 3 | 4 | 6 |
| FTR > 2 | 4 | 6 | 6 |
| **EQ** | **DET ∈<1;5>** | **DET ∈<6;19>** | **DET > 19** |
| FTR < 2 | 3 | 3 | 4 |
| FTR 2 | 3 | 4 | 6 |
| FTR > 2 | 4 | 6 | 6 |
| **EO** | **DET ∈<1;5>** | **DET ∈<6;19>** | **DET > 19** |
| FTR < 2 | 4 | 4 | 5 |
| FTR ∈<2;3> | 4 | 5 | 7 |
| FTR > 3 | 5 | 7 | 7 |

Table 3. Example of cost estimation with the method of summing, computing and evaluating

| Summed elements | Calculated number of objects [items] | Estimated Person per Month [h] | Total [h] |
|---|---|---|---|
| SQL queries | 14 | 6 | 84 |
| User interface windows | 8 | 3 | 24 |
| Printouts | 6 | 6 | 36 |
| | | Total | 144 |

Summing *UFP* values of all objects in all classes, the total value of unadjusted FPs is obtained (process 4 in Figure 4).

Value Adjustment Factor (VAF) considers the internal system complexity, unrelated to its functionality. Defining the value entails giving the impact of 14 factors, which may raise the system complexity (process 5 in Figure 4). The list of factors can be found in method documentation [31]. The estimation is done by an expert. Impact estimation requires attributing each of 14 categories with an impact factor from 0 to 5 (where 0 – no impact, 5 – strong impact). VAF value is calculated from formula (4):

$$\mathrm{VAF} = \mathrm{B} + 0{,}01 \sum_{i=0}^{14} C_i \tag{4}$$

where:

B – empirically determined constant value 0.65 [31],

$C_i$ – impact value of i-th factor.

On the basis of VAF, the final values of FPs are calculated by correcting the unadjusted FPs (process 6 in Figure 4) according to formula (5):

$$\mathrm{FP} = \mathrm{VAF} \cdot \mathrm{UFP} \tag{5}$$

Knowing the FP value, efficiency can be determined with two methods (process 7 in Figure 4):

- calculating into KSLOC with empirically determined values from the calculation table [32] and then using the COCOMO method to define PM
- if the organisation owns historic data, FP value can be directly calculated into PM, using Estimation by Analogy method.

The source of complete and updated documentation of the method is the website of International Function Point Users Group [33]. The idea of FPs was used in User Case Point [34] that is reliant on modelling agreeing with UML[6].

[6] UML (Unified Modelling Language) – a formal language used to model different systems, developed by the Object Management Group.

The condition of using FP is knowing the complete set of specific requirements. Thus, it can be used only from the stage of implementation analysis onward. The algorithm guarantees objective and repeatable evaluations. Unfortunately, the level of evaluation complexity, in comparison with non-algorithmic methods, is a barrier for its common use.

## 4 Non-algorithmic methods of software evaluation

### 4.1 Summing, computing and evaluating

The method concerns searching the available documentation (e.g. pre-implementation analysis, feasibility studies) and quantifiable objects, e.g. requirements, functions, use cases, stories, reports, windows, database tables and classes. Each identified object that can be summed is attributed (computed) with estimation constituent (cost or time). The estimated values are the function (6) of the objects constituting an information project:

$$f(x) = \sum_{i=1}^{N} C(x_i) \tag{6}$$

where:

x – calculated object,

N – the number of summed objects,

C – computer cost of the object.

An example of its use can be the valuation of developing a sales reporting module. If the authors managed to select the premises, such as SQL queries, interface windows, users and printouts, it is possible to define a unit PM. Thus, one can evaluate the costs of developing the whole module, as presented in Table 3

Table 4. An example of evaluation with individual expert evaluation method

| Valuated work | Most optimistic value [h] | Most likely value [h] | Least favourable value [h] | Calculated value |
|---|---|---|---|---|
| SQL queries | 45 | 81 | 108 | 84 |
| User interface windows | 14 | 22 | 32 | 24 |
| Printouts | 25 | 33 | 45 | 36 |
| | | | Total | 144 |

The cost of works depends on their value, in the above case, man hours in a given supplier's organisation.

The method is complex provided the source documentation allows determining the summed objects. One of the failures is the high risk of omitting objects or ranges of work that influence the value of the whole project, for example, ignoring supplementary tables or costs of developing filtering inquiries while evaluating the costs of interface windows. An important stage in this method is the evaluation of individual objects' costs. This can be done with individual expert evaluation method or group expert evaluation method. The method is efficient in projects with a small number of object types identified but are plentiful, e.g. 30 reports, 25 SQL inquiries and 18 interfaces. These types of data are infrequent in the stage of trade talks, but often present in feasibility studies and pre-implementation analysis.

### 4.2 Individual expert evaluation

The method of valuation by individual expert estimation is the most frequently used method, not only in software development [35], but also in other IT enterprises such as implementations and modifications. Research conducted in the USA in 2002 showed that as many as 72% of the valuations are done with this method [36]. In the first stage, the method requires selecting experts with appropriate knowledge and experience. Then experts evaluate the ranges they were bestowed. In order to reduce the evaluation errors, the method was modified with multiple evaluations for different versions of implementation. Such a technique, called PERT (Program Evaluation and Review) [15, 37], involves analyses of the most optimistic case, the most probable case and the worst case. However, it is different from critical path analysis (CPM [38]) because it is used to evaluate independent tasks only. After previous decomposition processes, the information about relations between tasks was lost. The expected evaluation has the following form:

$$f(x) = \sum_{i=1}^{N}(Cp(x_i) + 4 \cdot Co(x_i) + Ck(x_i))/6 \quad (7)$$

or, considering experts' tendencies to lower their evaluation:

$$f(x) = \sum_{i=1}^{N}(Cp(x_i) + 3 \cdot Co(x_i) + 2 \cdot Ck(x_i))/6 \quad (8)$$

where:

Cp – the most optimist value of the i-th task

Co – the most likely value of i-th task

Ck – the most probable value of i-th task

*N* – the number of tasks in the project.

Valuation of sales reporting module can be an example of the method. If the authors managed to select the premises, such as SQL queries, user interface windows and printouts, the expert can estimate the most optimistic, the most likely and the least favourable amount of work load. Then, one can determine the costs of programming work on the module (additionally, considering the inclination to lower the evaluation), as presented in Table 4.

The precision of results depends exclusively on expert's experience. The criteria of expert selection are determined imprecisely. The influence of personality has such importance that longer experience does not guarantee more precise evaluations. It happens that experts who are known for overvaluation or undervaluation are unpredictable.

### 4.3 Group expert evaluation

The method involves presenting the same range of work to more than one expert. In an unstructured version of the method (group review), the experts decide about the valuation or its range as a group. In a structured version called Wideband Delphi [15, 16], the experts' work is done in a formalised way and its result is a scoring evaluation.

Table 5. An example of valuing with the construction and decomposition method

| No. | Range of work | Estimated value [h] |
|---|---|---|
| A. | Preparatory work: | |
| A.1 | • software installation | |
| A.1.1 | - application server software installation | 5 |
| A.1.2 | - server database software installation | 4 |
| A.1.3 | - user software installation | 14 |
| A.2 | • database import | |
| A.2.1 | - export from "old" verification system | 8 |
| A.2.2 | - import to the new system | 11 |
| A.2.3 | - reconstructing indexes and data verification | 16 |
| A.2.4 | - back-up copy parameterisation | 2 |
| B. | Modification movement: | |
| B.1 | • modification movement in the area of finances | 34 |
| B.2 | • modification movement in the area of personnel | 21 |
| B.3 | • modification movement in the area of production | 120 |
| C. | Trainings: | |
| C.1 | • financial departments | 16 |
| C.2 | • HR department | 16 |
| C.3.1 | - hull production staff | 4 |
| C.3.2 | - wind station staff | 4 |
| | **Total** | **275** |

The work of experts in groups is more expensive than individual work; however, a method's advantage over individual evaluation is the decrease of personality factors' importance. In spite of different experience, characters and inclinations, experts will either reach a common ground or, as in case of Widebrand Delphi type, the conclusion of problem is reached by attributing pre-selected points. Wanting to minimise the costs of first stages of implementation, suppliers decide to engage a larger number of experts to do the same calculations.

The estimation method is used frequently at initial stages of IT projects in situations of high uncertainty of requirements.

### 4.4 Decomposition and reconstruction

Decomposition and reconstruction is a popular method due to its intuitiveness and universality. It is used in situations when whole project evaluation generates difficulties, e.g. resulting from work heterogeneity. In the practice of IT project implementation [29], there are very few projects that can be evaluated without this method.

The method involves decomposing the range into a number of components. The method of division is arbitrary and depends on project specifics. Consultants frequently undertake evaluation with the Work Breakdown Structure (WBS) method. Having done the division, the parts of objects are estimated and undergo further division with the same or another method. Even though the literature lists this method as equal to others [4], its role in the evaluation process is different. Project evaluation is started in this method, but after decomposition, other methods of elemental evaluation are selected. The depth of division depends on the method that is going to be used at another stage. A detailed description of decomposition method according to WBS can be found in literature [15, 39–42].

One example of this approach is the evaluation of IT system version change. The works can be decomposed in the manner presented in Table 5.

Table 6. Example of calculating multiplication index in evaluation by analogy

| Parts of decomposed project | Completed project [h] | New project (estimation) [h] | Multiplication index |
|---|---|---|---|
| Database table | 60 | 42 | 0,70 |
| User interface | 43 | 18 | 0,42 |
| Reports | 54 | 32 | 0,59 |
| SQL queries | 85 | 54 | 0,64 |
| Basic classes | 28 | 14 | 0,50 |

A significant element in this method is the manner of division. Suppliers with little experience in cost evaluation can do this division in a way that will generate significant errors in elemental evaluations. If the ranges of works in basic parts of the project are too excessive or heterogeneous in terms of the technology of development, the methods will generate unreliable results. The practice of modification estimation [29] suggests that the effects of decomposition method should be the works evaluated in a few or a dozen man hours.

### 4.5 Evaluation by analogy

This method involves dividing the project into components that already exist in a completed project. Evaluating the selected parts, one may calculate the ratio of two project sizes (new and the completed one). Knowing the relations between the sizes and the costs of the completed project, one may estimate the value of the new project.

One example of this method is presented in Table 6. The average multiplication factor for the above example is 0.57. Knowing this result and the value of the completed project, one can estimate the value of works.

The difficulty lies in collecting historic data from similar projects and structure as the evaluated project. An additional problem is the selection of a representative part of the decomposed project, which is a basis for multiplicity factor. Ignoring significant objects may increase the evaluation error.

The input data for this method come from project documentation, e.g. interfaces, reports and SQL queries. Only for this type of objects can the multiplication factor be calculated. The use of requirements, even the specific ones, does not allow for calculating the multiplication factor, and thus the whole evaluation must be performed. Evaluation by analogy is also used to calculate PM on the basis of FPs.

### 4.6 Valuation based on substitution

Similar to the previous method, this method requires the knowledge of costs of previously completed projects in the organisation of standard objects (interfaces, reports, etc). Depending on the version of method, the objects can be grouped differently. For example, Putnam [37] and Humphrey [43] selected different classes of objects: very small, small, medium, large and very large. Another method of classifying the objects is a standard component method [4] used to evaluate object software. The division can then be as follows:

- dynamic WWW websites,
- static WWW websites,
- data tables,
- reports,
- business rules.

If the IS system supplier uses extreme software or close to Agile methods [44], the so-called “stories” might be a standard element.

Then, the groups of objects are attributed with average cost values, e.g. number of lines of code, man hours or man days. The objects from a new project must be classified in the same manner. Then their sum can be calculated.

An example of such an approach is the project of white goods’ sales. The cost estimation is presented in Table 7.

Table 7. An example of valuation by substitution

| Standard classes of components | Average value of costs [h] | Number of objects in a class | Value of costs [h] |
|---|---|---|---|
| dynamic WWW websites | 7 | 5 | 35 |
| static WWW websites | 2 | 18 | 36 |
| data tables | 7 | 16 | 112 |
| reports | 5 | 9 | 45 |
| business rules | 12 | 5 | 60 |
| | | Total | 288 |

The supplier determines the average cost of works in a given class, e.g. the cost of building one static website – 2 man hours – on the basis of previous historic data. In a new project, the works are attributed with appropriate classes, e.g. dynamic websites – 5 pcs. Reports – 9 pcs. Then the old objects are substituted with the new ones.

It is only the experienced organisations that are able to use this method. Not only does it require having historic data but also weights must be attributed to them. One should remember that the weights will be valid only till the developer's tools or programming style is changed.

As in the previous method, this should be used when classes of programming objects are known. One exception is the organisations using extreme or agile software. In this case, the cost of "stories" documented at the stage of talks to clients may be substituted with historic data. The practice of evaluations [29] indicates that the method can be incidentally used at an earlier stage (pre-implementation analysis), when only the requirements are known.

## 5 Conclusions

In conclusion, one should notice that implementation of the first stages of software lifecycle provides more and more information about the planned solution, on the one hand, and there are a number of evaluation methods available, on the other.

At the stage of trade talks, the supplier holds a complete list of client's requirements. The set includes general requirements, a few specific requirements and a subset of undisclosed requirements. Specific requirements, such as specific printouts, reports and inquiries, may be evaluated in summing, computing and evaluating method. Other requirements, especially undisclosed ones, will be appropriate only for the individual expert method and group expert method. Experts, who have historic knowledge, may predict that if the client specifies one requirement, it will implicate a set of other functions that might be revealed only at another stage of works.

After completing feasibility study or a pre-implementation analysis, the suppliers hold a complete set of specific requirements. COCOMO methods are used in case of lack of reasons for using KSLOC. For *FP* analysis there are sufficient input data. Summing, computing and evaluating and evaluation by substitution can be used in project valuation; however, using requirements as input data will generate significant errors. Individual expert analysis and group expert analysis with complete requirements generate significant errors in results. At this stage, it is too early for evaluation by analogy because requirements as input data will generate errors.

Project of changes provides additional information related to implementation – data structure, information on processes, objects and so on. Only from this stage can KSLOC be estimated in order to use COCOMO method. For summing, computing and evaluating and evaluation by substitution methods, input data significantly limit the errors of results. Only at this stage can evaluation by analogy be used. For other methods, the quality of estimation is increased only slightly by including additional data. For individual expert analysis and group expert analysis, the data taken in project documentation are inappropriate. Deliberate use of these methods causes significant errors.

By classifying the possibility of using evaluation methods in the following way, we can present them in a table (Table 8):

0 – impossible to use, lack of data,

1 – usable but generating significant errors, because the data are inappropriate,

2 – usable and generating satisfactory results

Table 8. Usefulness of evaluation methods

| Method \ stage | Trade talks | Feasibility study / pre-implementation analysis | Project of system changes |
|---|---|---|---|
| COCOMO | 0 | 0 | 2 |
| Function point analysis | 0 | 2 | 0 |
| Summing, computing and evaluating | 1 | 1 | 2 |
| Individual expert analysis | 1 | 2 | 0 |
| Group expert analysis | 1 | 2 | 0 |
| Evaluation by analogy | 0 | 0 | 2 |
| Evaluation by substitution | 0 | 1 | 2 |

An alternative use of the evaluation method is presented In Figure 6. Because method usability depends on input data, quality and type of requirements and project components can be the basic criteria for choosing a given method.

Due to different characters of elements constituting IS (business rule software, data interface software, reports, etc), evaluation of cost and implementation time should start with decomposition of work into tasks and groups of tasks. Then, still in the phase of trade talks, they can make attempt evaluation by experts (group of experts), if the data obtained from client are of appropriate quality. If specific requirements are identified, the supplier can additionally use summing, computing and evaluating method.

Fundamentally, the data of quality that allow for evaluation of cost and implementation time are obtained in subsequent stages, i.e. feasibility study and pre-implementation analysis. Then, *FP analysis* or *evaluation by analogy* can be used.

At the system development stage, the analysis of implementation costs can be based on very detailed data, and thus it is burdened by serious errors. The array of methods can be supplemented by *evaluation by analogy* or COCOMO.

The methods of selecting the manners of evaluating costs of IS implementation in the context of input data quality are going to be the topic of future research. The authors will also search for methods for quick definition of precise input data, even before the stage of feasibility study.

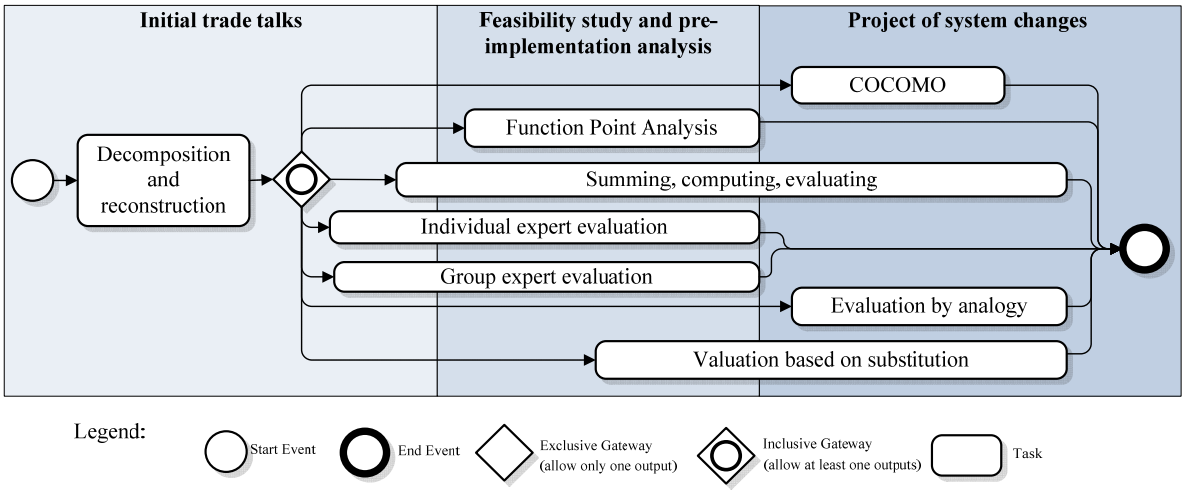


Figure 6. Suggestion for an alternative use of evaluation methods. COCOMO, constructive cost model

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# THE RESOURCE HAZARDS MODEL FOR THE CRITICAL INFRASTRUCTURE OF THE STATE EMERGENCY MANAGEMENT PROCESS

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***Abstract:*** This paper presents an investigation of the relevant factors related to the construction of a resource model which is designed to be useful in the management processes of the operation of critical infrastructure (CI) for state emergencies. The genesis of the research lay in the perceived need for effective protection of multidimensional CI methodologies, and it was influenced by the nature of the physical characteristics of the available resources. It was necessary to establish a clear structure and well defined objectives and to assess the functional and structural resources required, as well as the potential relational susceptibilities deriving from a number of possible threats and the possible seriousness of a specific range of incidents and their possible consequences. The interdependence of CI stocks is shown by the use of tables of resource classes. The dynamics of the interaction of CI resources are modeled by examining how using clusters of potential risks can at any given time create a class of compounds related to susceptibilities and threats to the resources. As a result, the model can be used to conduct multi-dimensional risk calculations for crisis management CI resource configurations.

***Keywords:*** resource, resource features, class of resources, threats and susceptibilities of the class of resource, critical infrastructure system (CI system), positioning resources of CI**,** hazards cluster.

## 1 Introduction - the genesis

(...) *We assume every day the right to freedom, knowledge and security - not necessarily realizing this fact. Human work related to the environment has accumulated many cultural resources over a number of centuries, including such modern resources such as power plants, banks, universities, insurance, health care, computer networks, databases, plastic cards of various types, markets , subway stations, gas stations ... these are apparently endless, but in fact they are countable sets of surrounding resources, services and opportunities. This is due to the diversity of resources that can be organized in a related administrative infrastructure territorial state* (...) [1].

Part of this infrastructure, which is created to ensure the safety of human life, is known as critical infrastructure (CI)[1], and can be systematically encapsulated in specific physical and methodical protection. The purpose of physical protection is to ward off internal and external threats[2] in order to isolate structural and functional CI. The purpose of carrying out methodical systematic risk estimations and the maintenance of CI resources was to assess threats and susceptibilities and to prevent and minimize the level of a single incident, a group of incidents and incidents that turned into a crisis. In the following discussion the focus is placed mainly on methodical protection.

The Act of 26 April 2007 on crisis management, hereinafter referred to as the *Act*, imposes an obligation to draw up plans and reports on national security. One of the most important reports is the report on threats to national security developed to the requirements of the *National Crisis Management Report*[3], hereinafter referred to as the *Report*, wherein

[1] The Act of 26 April 2007 on crisis management (Journal of Laws of 2013 pos. 1166) defines critical infrastructure (CI) as follows: "*Art 3 Whenever in this Act: (...) 2) critical infrastructure - should be understood as systems and their constituent functionally interrelated objects, including building structures, equipment, installations, services essential to the security of the state and its citizens required to ensure the smooth functioning of the public administration, as well as institutions and entrepreneurs. Critical infrastructure includes: a) the supply of energy, raw materials and energy consumption, b) communication, c) ICT networks, d) the financial, e) the provision of food, f) water supply, g) the protection of health, h) transport i) rescue, j) ensuring the continuity of the public administration, k) the production, storage, handling and use of chemicals and radioactive materials, including pipelines containing hazardous substances* (...)."

[2] The threat is a phenomenon caused by the interaction of human, material objects or phenomena, leading to increased risk of adverse events, and in the case of a significant worsening of their well, to an emergency.

[3] Council of Ministers of 30 April 2010 on the report of threats to national security (Journal of Laws of 2010 No. 83, item. 540).

the coordination of the preparation is provided by the Director of the Government Security Centre (GSC)[4].

The main objectives of the *Report* are to identify the most important national security threats and assess their risks. The document contains strategic objectives and projects that should be implemented in order to minimize the possibility of hazards and their effects.

After analyzing all of the information in the *Report*, it appears to be necessary to develop a model of CI information for possible risks in order to provide a single, multi-dimensional and objective description of them. Model information risks CI could be used to support decision-making in crisis management. Information Model CI threats could also be useful for the construction of the so-called system of methodical CI resource protection, as they cover all the stages of crisis management, including:

- collection and aggregation of operational data about the state of the CI,
- analyzing and reporting the status of threats to the CI,
- operational management of a crisis,
- planning and strategic management to ensure the safety of the state.

## 2 Purpose and structure of the research

To make methodical resource protection IK possible, it is necessary to conduct systematic modeling and analysis of the structural-functional compounds which appear in a CI and its environment. For this purpose, the administrative structure of the state creates a virtual network of nodes and relationships administrative, whose task is to monitor the resources required for CI, on the basis of systematic analyses of threats, susceptibilities and risks of impacts (events). Virtual nodes are divided into: operational nodes (representing physically separate resources CI), intermediate nodes corresponding to the administrative structure of the state (municipalities, counties, provinces) and the central node.

In order to test the effectiveness of methodical protection, it is necessary to prepare a unified conceptual and algorithmic apparatus which can be used to:

- describe the dynamics of the characteristics of resource sharing in relation to the characteristics of risks and susceptibilities in the nodes of the operating networks,
- calculate the potential risks and potential susceptibilities in the operational, intermediate and central nodes,
- calculation of the risk of incidents, groups of incidents and crisis events,
- build a simulation model of a virtual network of nodes and links to assess various administrative issues, in order to monitor and consolidate the characteristics of the potential risks and potential susceptibilities of online network nodes,
- build a model of decision-making for virtual networks of nodes and create administrative links which are capable of supporting hierarchical decision-making CI administrators in the minimization of the risk of incidents and the liquidation of the consequences of their occurrence.

The main objective of the study is to prepare a methodology for assessing the risk of a crisis, in particular the destruction or disruption of CI. During a detailed analysis of risk assessment issues emergencies, one of the most difficult problems turned out to be developing comprehensive procedures that:

- enable the collection, aggregation and processing of data about threats in all the distinguished systems of CI,
- take into account the interaction of the threats posed by CI and their consequences in the form of a domino effect in the relationship between CIs and CI relationships with the environment,
- allow for modeling and generating forecast threats which may be spread in internal and external CI environments,
- are consistent methodically at all levels of crisis management CI,
- can be used for the development of planning documents and reports of research internships for crisis management CI.

In order to achieve this objective, there needs to be:

- an assumption that the areas of critical infrastructure are created by class resources that are vulnerable to threats from other resources and are themselves a threat to the resources in their environment,

[4] The Act of 26 April 2007 on crisis management (Journal of Laws of 2007 No. 89, item. 509, Art. 5a).

- a listing of the characteristics of the classes of resources on the basis of their susceptibility, and of the risk they create for the CI resources of their surroundings and the proposed positioning of the resources in time and space, taking into account the geographical distribution of resources and their destructive effects on other resources, as the threats and, consequently, the risks depend on the configuration of resources and their potential impact.

In order to develop comprehensive crisis management tools, CI is necessary to formulate guidelines to construct a model based on dynamically developing interactions (incidents) within and between CIs. It was assumed that the proposed model would be based on the decomposition of CI resources, taking into account the correlation (coincidence and synergy) of the relationship between CIs in the event of a threat. Such an approach should enable the modeling and analysis of the spread of incidents in and between CIs, and may be relevant to the overall assessment of the risk of a crisis in a functioning CI.

A model based on dynamically developing interactions (events) between CI resource approach was applied [7], involving the decomposition of CI in clearly distinguishable classes of stocks including:

- proposed repertoires characteristics (attributes) of resources,
- the criteria for the selection of the characteristics of resources,
- proposed principles of mutual positioning of resources in the CI, which are important to indicate the impact of a full or partial loss of the resources to threats in other resources belonging to CI.

This approach allows for the identification and assessment of susceptibilities and threats to CIs, the identification and analysis of interdependencies of a geographic nature, and between CI systems. It is anticipated that the model will be used to prepare the system at any level of crisis management to enable the collection of operational data about the state of CI, the aggregation of the data collected and the analysis and to report the status of threats and emergencies related to CI.

In work is intended to:

- present selected elements of the theory of resources (Section 3), as a basis for the interpretation of the classes and the critical infrastructure of resources,
- clarify the concept of CI and the CI system (Section 4),
- formulate guidelines for the construction of a CI model, assuming that CIs are created by class resources that are vulnerable to threats from other resources and are themselves a threat to the resources in their environment,
- identify the characteristics of the classes of resources offered by the specification of the characteristics of their susceptibility to hazards and dangers,
- propose the positioning of resources in time and space by taking into account the geographical distribution of resources and timing their destructive impacts on other resources, assuming that the consequent risk depends on the configuration of resources and timing of their interactions,
- specify an initial proposal for a repertoire of attributes that can be harmonized for all critical infrastructures, which would allow the development and use of the same tools for collecting operational data, the reporting and aggregation of data and the conduct of analytical and decision support.

## 3 Elements of the theory of resources

The concept of a resource is regarded as a universal term, in the place of which the name of the highlighted item (real or abstract) of the modeled reality is substituted. A resource can be “something” or “someone”. Resources can have a structure can be described as a set of attributes (features) which overlap between specific compounds. It is possible to specify the class of resources to which they belong and the sets of attributes of their individual values for each resource belonging to their specific class. The analysis conducted in this part of the article reflects on the trading of resources, the dynamics of the processes carried out by the resources and decision-making processes, the associated resources and their interaction processes.

The aim of the analysis is to identify structural-functional phenomena for the effective implementation of and management of their resource decision-making processes. The efficiency of particular resources is evaluated based on the criteria of balance, ensuring the desired states of structural-functional relationships in distinguished categories of critical infrastructure.

The considerations are carried out from three perspectives: *resources*, *processes* and *decisions*. These perspectives are interwoven in order to allow their mutual interpretability and coherence in the course of analyzing the results of the theoretical and practical aspects

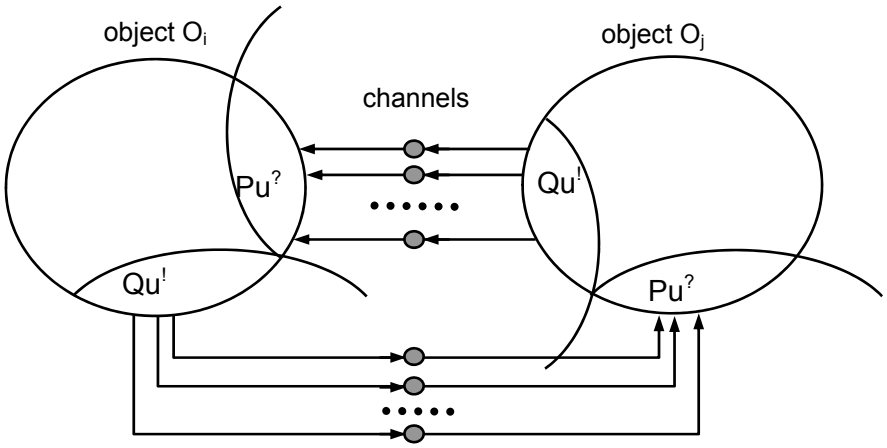


Figure 1. Mutual activities of the two resources - output channels of threats and input channels of susceptibility objects Oi, Oj

of the structural-functional phenomena being observed. Other research perspectives on integral assessments of potential impacts (e.g. risk factors), risk assessment and situational management (crisis management) will be included, using unconventional operating systems, game theory, semiotics, Pavlovian networks, theories of catastrophe and other research methods.

The key assumption is that of the methodological coherence of models, guaranteeing their co-operation in specific technological layers of a crisis management system.

The prospective "*resources*" make possible a resource-oriented (static and dynamic) interpretation of interacting fragments of physical reality and information. The task here is to identify all the objects in this reality which are essential for maintaining the desired balance.

The prospective "*processes*" show the dynamic processes of recognition of objects in the course of their interactions. The construction and analysis of the processes taking place in the objects and between objects can be used to define and solve decision problems related to the maintenance of the desired objects in a state of equilibrium.

The prospective "decisions" relate to the definition and decomposition of decision problems, which should lead to the determination of the trajectory of the desired parametric resource states in the process of the setting up and interaction of objects.

The material presented is the result of the selection of a group of systemic issues that can be presented in a form that does not seem to be too simple and also does not require the use of excessive abstract notation. Among the topics were selected elements of an engineering and utility that can be used for modeling and designing systems and the nature of organizational and technical information, in order to help define the roles of people and resources.

The condition of effective coordination of resource interaction is necessary to recognize the morphological characteristics, and above all the functions, structure and transformation of these characteristics. Well-constructed ontology area interactions can significantly affect the architecture (spatial structure) and function (efficiency) crisis management system.

For the purpose of resource configuration, the analysis is treated as a collection of object related channels, wherein the channels play a key role by which the objects communicate with each other. Channels correspond to those objects, and the values of their states correspond to the current values of the attributes of the resources. An illustration of the mutual activities of the two resources is Fig. 1, which shows two related object channels.

The susceptibility of objects $O_i$ and $O_j$ is modeled by susceptibility function systems (observation) Pu. Threats of objects $O_i$ and $O_j$ are modeled by functions threats systems (extortion) Qu.

Channels act as storage facilities - and if detailed description is necessary - they can be interpreted as objects, thus creating a multi-layered model of resource configuration. The phenomena occurring in the channels of the object are treated as processes of risks and susceptibility. It is assumed that any operation of the object can be described by sequences of discrete events that enforce and control the repertoires of finite state channels.

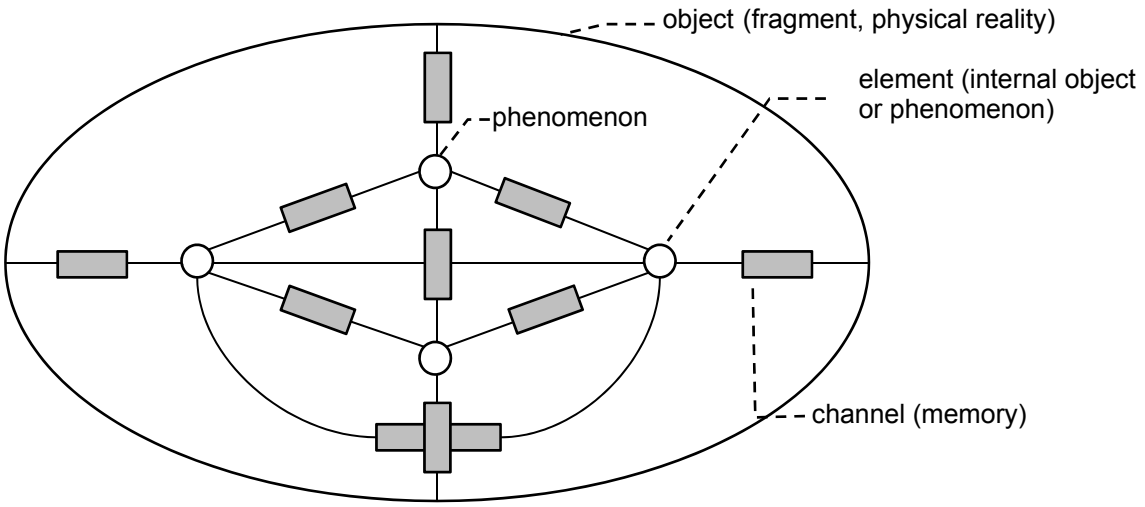


Figure 2. Object and its elements connected with channels as a model of particulars and phenomena

The concept of the object can also be used to describe physical reality, and in rare cases to the description of the corresponding unstable virtual reality. The facts are also used to describe phenomena (interactions) in them or between them occurring. The concept of the object is used to model the structure constant during each of the interacting fragments of material reality. The concept of phenomenon is used to describe the effects of the interaction of objects.

The discussion may include occasions when the concrete can take the form of material - for example, highlighting the physical condition of the channel or information form - such as a data record stored in the buffer memory.

With such facilities, *class invariants* (invariants) and meta-language descriptions of physical reality can be constructed. Fig. 2 illustrates the three levels of modeling (object - element - impact) and analyzing fragments of physical reality. Processes occurring in physical reality may be presented at the level of meta-language descriptions of the particulars and phenomena, if the only concrete fact assigns the element related channels into a single object. In this description, the channels are used to model the interaction of particulars. In this interpretation, the impact of particulars are presented by the relationship of mutual threats and susceptibilities recorded on the channel connecting material objects (particulars) and other related phenomena.

## 4 Positioning resources - the interdependence of CI

The use of the resource approach makes it possible to define critical infrastructures as systems including their constituent functionally interrelated objects, such as building structures, equipment, installations, services crucial to the security of the state and its citizens and to ensure the smooth functioning of the public administration, as well as institutions and entrepreneurs.

As stated in the National Programme for Critical Infrastructure Protection (NPCIP): "*Identification of facilities, equipment, installations or services whose destruction or disruption of the operation would cause a crisis, is a key step in the process of protecting CI*." Part of NPCIP's proposed method for identifying critical infrastructure uses identification criteria for each CI system, describing them as criteria for the systems. These criteria quantitatively or subjectively characterize parameters (functions) resources (objects, devices, systems or services), which are suitable for resource allocation to critical infrastructure. This approach allows for a definition of the critical infrastructure of the simultaneous decomposition of CI systems and constituent resource classes, which can also be considered as part of the CI in the system, as illustrated in Fig. 3.

The CI system is built in accordance with the representation of the concept. For each operational area R (e.g. municipalities) are specified as real property, equipment, installations, and other systems belonging to various classes of CI and their resources (Fig. 4).

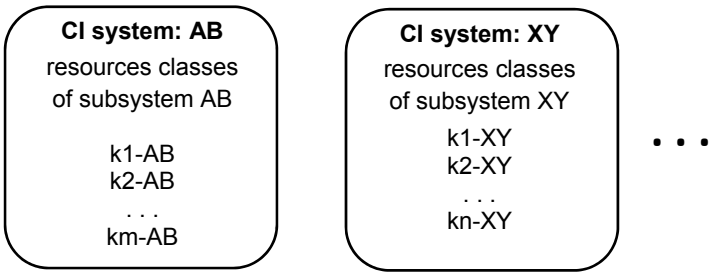


Figure 3. The decomposition of CI systems
and their constituent classes of resources

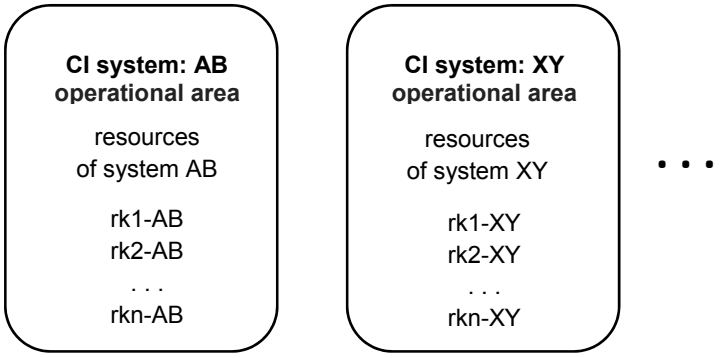


Figure 4. The resource features in the operating areas rk*i* of CI systems

Table 1. Classes of resources in the CI systems

| resource | CI system (CIS) in operational area R | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | AB | BC | CD | DE | EF | FG | GH | . . . . . | | | XY |
| rk1-AB | 1 | | 0,5 | | 0,1 | | 0,2 | | | | |
| rk2-AB | 1 | | | 0,1 | | | | | | | |
| . . . | 1 | | | | | | | | | | |
| rkn-AB | 1 | 0,4 | | | | | | | | | |
| rk1-BC | | 1 | 0,2 | | | 0,2 | | | | | |
| rk2-BC | | 1 | | | | | | | | | |
| . . . | | 1 | | | | | | | | | |
| rkn-BC | | 1 | | | | | | | | | |
| . . . | . . . | . . . | . . . | . . . | . . . | . . . | . . . | . . . | . . . | . . . | . . . | . . . |
| rk1-FG | | 0,2 | | | | 1 | | | | | |
| rk2- FG | | | | | | 1 | | | | | |
| . . . | | | | | | . . . | | | | | |
| rkn- FG | | | | | | 1 | | | | | |
| rk1-GH | | | | 0,2 | | | 1 | | | | |
| rk2- GH | 0,1 | | | | 0,3 | | 1 | | | | |
| . . . | | | | | | | . . . | | | | |
| rkn- GH | | | | | | | 1 | | | | |

Table 2. Classes of resources in the CI systems

| | AB ⇩ | BC ⇩ | CD ⇩ | DE ⇩ | EF ⇩ | FG ⇩ | GH ⇩ | . . . . |
|---|---|---|---|---|---|---|---|---|
| AB | | | | | | | | |
| BC | 0,4 | | | | | 0,2 | | |
| CD | 0,5 | 0,2 | | | | | | |
| DE | 0,1 | | | | | | 0,2 | |
| EF | 0,1 | | | | | | 0,3 | |
| FG | | 0,5 | | | | | | |
| GH | 0,2 | | | | | | | |
| . . . . | | | | | | | | |

Individual CI systems are interrelated and interdependent. Many CI systems realize their functioning due to the availability of resources contained in other systems of CI. This relationship can be represented as a table: CI resource systems (Table 1).

Resources belonging to a particular CI system are represented by the value 1.

The estimated impact of a resource on the functioning of the other CI systems is indicated by parameter values in the range of 0 to 1. An analysis of parameter values and their distribution, as presented in Table 1, is used to determine the resource position of critical infrastructures, both in terms of scope and strength of their impact on other CI systems.

Analyses of parameter values and their distribution in Table 1 are used to determine resource positions in critical infrastructure, in terms of both the scope and strength of its impact on other systems CI.

Based on the data entered into Table 1 it is possible to determine the interdependence of CI, including the extent of mutual dependence.

In Table 2, the rows and columns of the table refer to the individual CI systems. The values entered in the table cells indicate the degree of impact of the CI system as indicated in the column header whereby CI systems are placed in the rows on the table. It can be seen, for example, that the CI system AB is indicated as the impact on the functioning of the BC, CD, DE, EF, and GH, but that it is not itself susceptible to disturbances caused by the reduction or absence of the operation of the other systems. The BC may cause harmful interference to systems CD and FG, but is prone to interference from both the AB and FG.

Information about the mutual interdependence of CIs can be useful when making decisions during crisis management.

## 5 Resources and hazards clusters

Resource taking (in a “more or less” controlled) way of the effects of threats in the coming months from resources with regard to location, processing, remembering and communicating in the form of further threats (extortion) and adjacent resources.

An analysis of this process may be important for understanding the phenomenon of pyramidal dominos in the spreading of threats and emergencies.

Fig. 5 shows two models of hyper graph clusters resulting in risks of structural transformation of resources that have moved relative to each other (stock-components are shown as hatched circles) and which initiated the creation of negative interactions within these clusters.

Hyper graph arcs indicate the direction of the threats (negative interactions) between resources. One of the arcs illustrates the risk-return “self-destruction”. Some of the arcs indicate the risks posed by the resources deployed in the interior of the structure of other resources.

In situations of real threat, the nature of CI resources and CI systems interdependence should be considered by taking into account the dynamics of movements of resources (direction, time, and potential threats or susceptibilities). For this reason, each distinguishable resource belonging to the CI system should be interpreted as “a cluster of risks”.

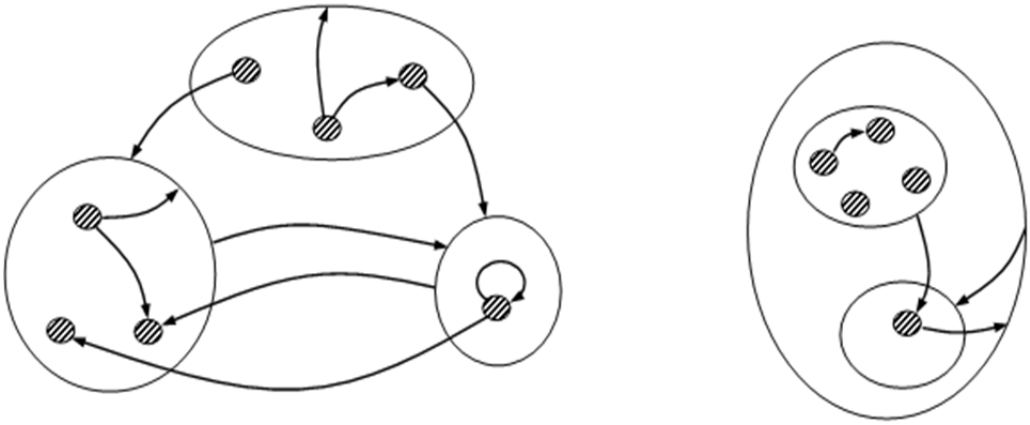

Figure 5. Hyper graphs clustering models of risk

In Fig. 6 the configuration of the cluster resource risks is shown. It is possible that each resource $R_i$ may contain in its distinguishable structure other CI resources which should be treated as a cluster risks. Resource interactions $K_{i,j}$ are represented and transformed in the form of channels in which threats and susceptibilities are processed and balanced.

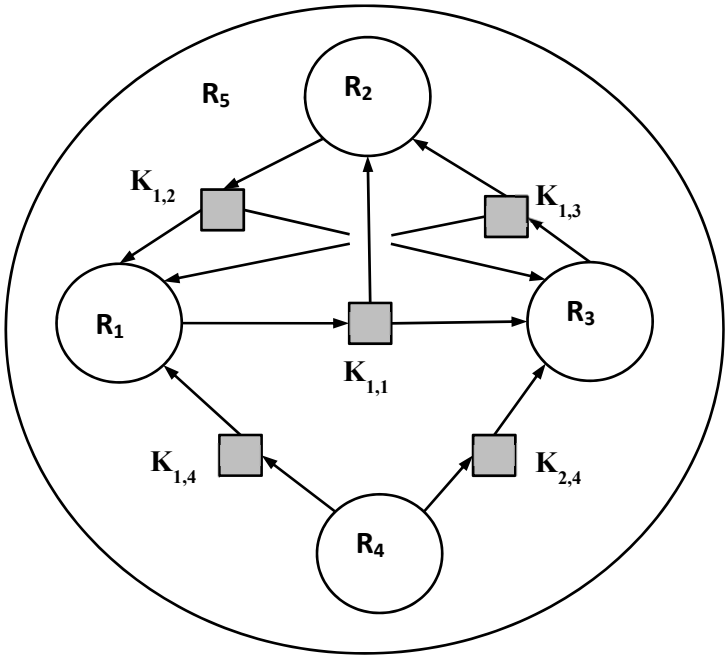


Figure 6. The cluster resource configuration

## 6 Susceptibilities

Concepts of susceptibility and susceptibility analysis usually arise in the context of IT technology. Information resources, including data often strategically located in the IT infrastructures of organizations, are susceptible to a number of internal and external risks. Identification of critical resources and analysis of their susceptibility makes it possible to evaluate the effectiveness of current safeguards and formulate proposals for solutions to improve their safety.

Topic susceptibility has been taken in many environments after 11 September 2011, when a terrorist attack highlighted the susceptibility of many systems at risk, which were not expected, using procedures that would allow for reducing the effects of hazards.

The analysis of critical resources and potential threats seems to be insufficient. The effects of the same risks in relation to the resources of the same class may be very different due to the varying susceptibilities of resources to the same threat.

Conclusions from the analysis based on risk and susceptibility to the threat of resources:

1) Resources of a particular class, included in the critical infrastructure have established repertoire of already differentiated features (Fig. 7).

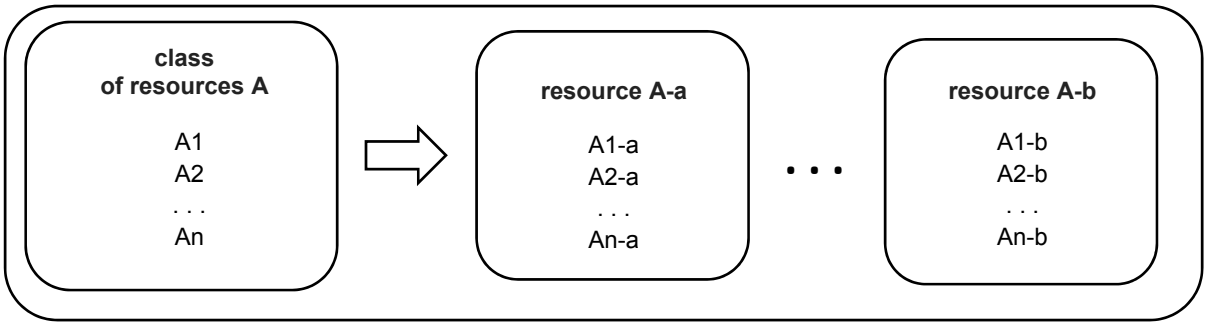


Figure 7. Class of resources

2) A fixed subset of a class of resources determines their susceptibilities to the threat to specific resources (Fig. 8).

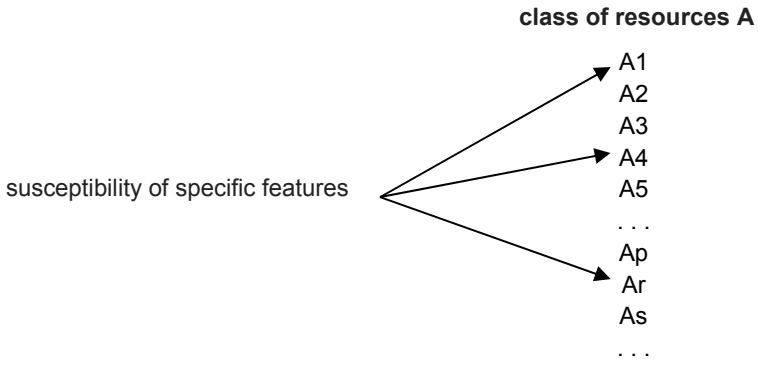


Figure 8. Susceptibilities of class of resources A expressed by the values of the features

3) With each threat a resource assesses susceptibilities to it, so each class of resources will also have a corresponding list of susceptibilities (Fig. 9).

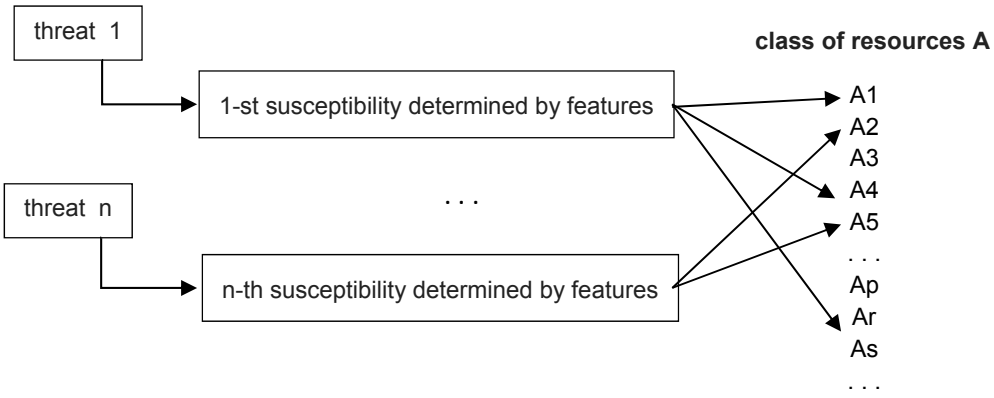


Figure 9. Threats and susceptibilities of the class of resource A expressed by the values of the features

4) It seems that susceptibility is a function of the features and will be distinctive and individual for each resource in terms of its value - and does not use the same class of resources with different characteristics (Fig. 10).

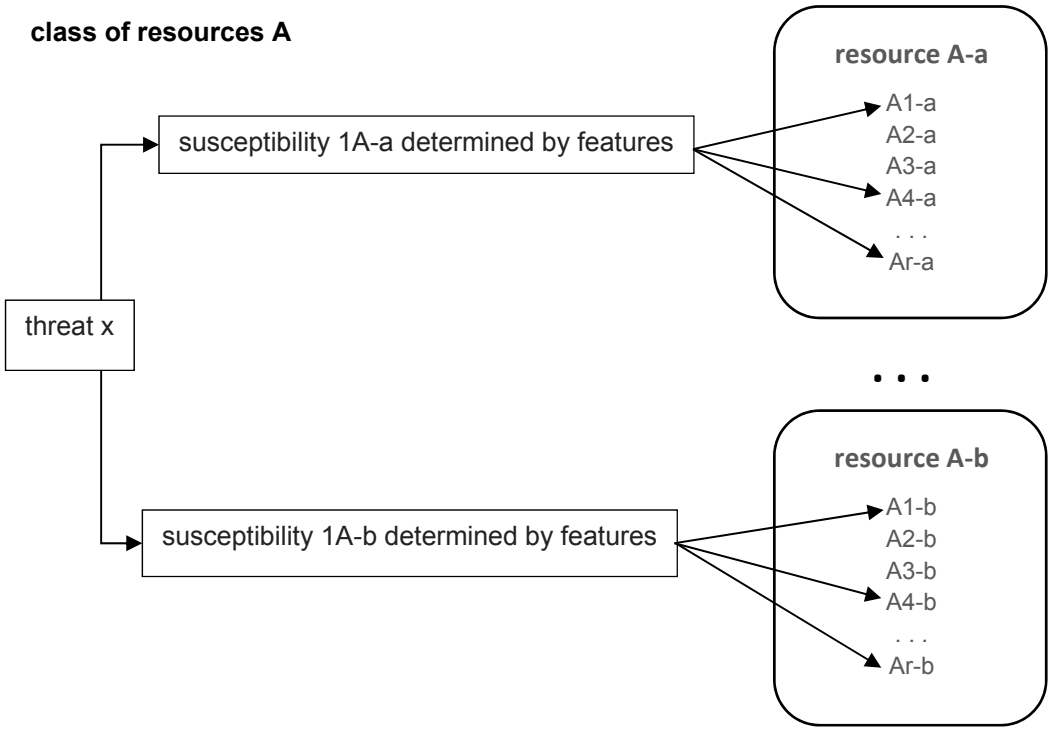


Figure 10. Relationship "threat x - susceptibility class resources" expressed in the values of the features

5) The specific features of the object determine its susceptibility to risk and their impact on the susceptibility can vary considerably. It thus seems necessary to position the characteristics of resources in terms of their susceptibilities to risk (Fig. 11). It may be that susceptibility analysis procedures assume that the sum of the weights should be 1 - similar to modeling problems, decision areas and decision-making processes [3, 4, 6].

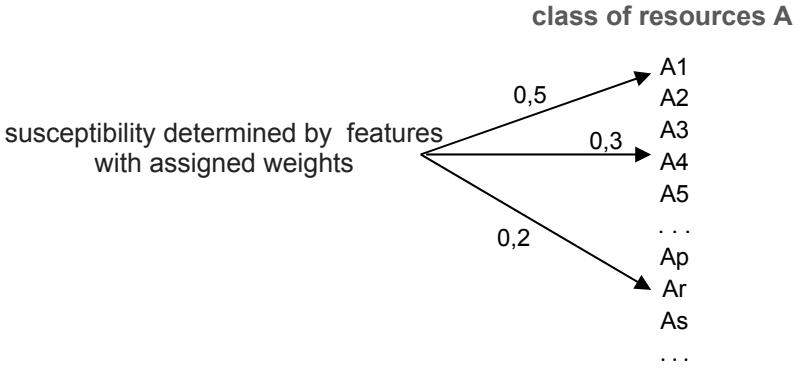


Figure 11. Susceptibility of the resource expressed using weights assigned to groups of features

6) The values of the resource attributes can change over time, which makes it possible to change the susceptibility of resources to a threat by means of established policy changes to its characteristics. It should, however, be noted that changes in the value of certain features associated with different resource susceptibilities may cause a reduction of one form of susceptibility while increasing others. With the change in the value of individual features, adjustable sensitivity class share resources can be weighted assigned to groups of features (Fig. 11 and Fig. 12).

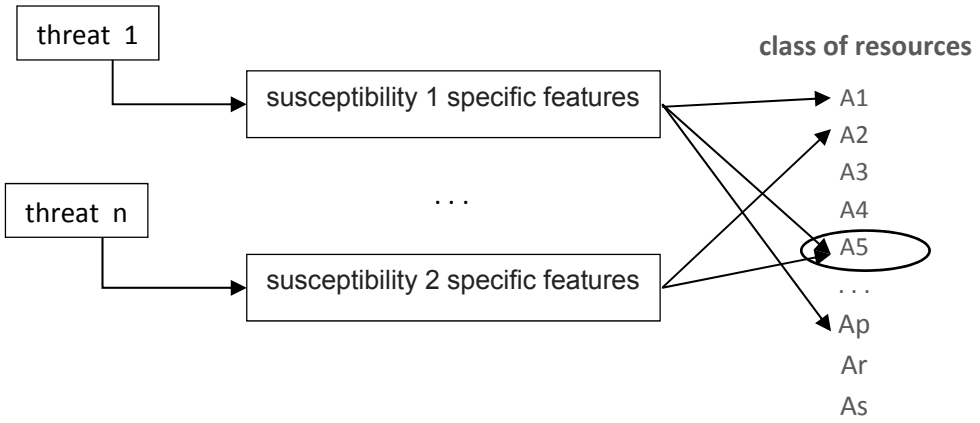


Figure 12. Illustration relationship threats and susceptibility Class A resource expressed in the values of the features and weights are assigned to groups of features

7) Since the values of various characteristics may vary over time as a result of threats or due to business resources of the owners, the changes may involve additional susceptibility. Such values may change rapidly, and should be determined in real time, which is only possible with the support of IT tools.
8) Susceptibility to risk may also arise from the interdependence of resources as a result of the overlapping of critical infrastructures and mutual threats posed by the domino effect.

## 7 Summary

The interpretation of critical infrastructure in terms of resources allows the use of a simple conceptual apparatus to describe the complex question of the identification of CI systems, which is the basis of specific actions related to national security. In the course of further work this provides a critical analysis of infrastructure systems in terms of their resources. Test specification attributes are required in the process of reporting, analysis and decision-making as well as activities related to the provision of national security.

The proposed approach allows the interpretation of all the data required to prepare the report on the dangers in the category of resource characteristics of critical infrastructure. This includes data on resources and data, from which information about mutual interdependencies of resources can be obtained, as well as data about the dynamics of changing times under the threat of deliberate action by the owner or resources including, for example, changes in the characteristics of the resources that reduce susceptibility.

The inclusion in the model of the characteristics of resource susceptibility to hazards can be used to:

- assess the effectiveness of current security and of possible changes in reducing susceptibility to specific risks and increasing safety parameters in the area of critical infrastructure,
- assess risks in the form of a risk account for which various features contribute to the increasing susceptibility of resources at risk.

In the course of further work a multidimensional information model of CI is planned, combining a description of the dynamics of susceptibility and threats to CI systems.

The expected result will be the ability to conduct effective risk calculation for crisis management of CI resource configurations.

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# IMPLEMENTATION OF BUSINESS INTELLIGENCE IN AN IT ORGANIZATION – THE CONCEPT OF AN EVALUATION MODEL

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***Abstract**:* This paper presents the issue of assessing the validity and effectiveness of implementing a Business Intelligence system in an IT Support Organization. This entity provides IT services to external clients involving, in particular, the storage and processing of large amounts of data. The vast amount of realized projects and also incidents reported in connection with those projects prevented effective decisions from being made without the support of dedicated technologies. The authors present the problems encountered by the studied entity and describe the tool that was selected to improve the situation. The aim of this study is to measure and describe the key processes in the organization on the basis of prepared aggregated measures, first prior to the implementation of the BI system and then a year after its implementation. The evaluation model developed by the authors allowed the assessment of the key aspects of the company's operation over 2 years. It thus helped decision makers to establish whether the decision to implement the Business Intelligence system was correct or not.

***Keywords:*** Business Intelligence, IT support organization, decision-making, evaluation model.

## 1 Decision-making issues in IT organizations

Over the years, the amount of data needed by organizations for their proper functioning has grown considerably. The history of portable data storage devices is an excellent example of this. At the beginning of the 1990s, a floppy disk with <1.5 MB capacity was sufficient for most needs; at times, it was necessary to use several disks. A few years later, the CD appeared, which at that time had an unimaginable capacity of 700 MB. But this also proved to be too little – another leap forward in the form of DVDs increased the available portable storage capacity by more than six times. Today's portable memory sticks are smaller than a matchbox, and yet allow a few (or a few dozen) times more data to be stored than a DVD.

With the increase of available disk space, data management skills have been lost – why would anyone bother about three identical copies of the same file if hundreds of gigabytes of free space were still available? For home users, this is not such a big problem. However, what happens when the same approach is carried out by a company that uses hundreds of computers? The demand for available memory is growing rapidly and the cost of infrastructure is rising with it. It should also be noted that although data are collected for a specific purpose, obtaining the necessary information from it is often very difficult. When it comes to taking strategic decisions, it is then necessary to manually analyze multiple sets of data (files) and draw conclusions from them. Such a painstaking search rarely gives measurable results.

In principle, the decision-making process is performed in several steps: defining the problem, examining the options, predicting the consequences and choosing the optimal variant [1]. The first one is often problematic, especially in the aforementioned case of data excess. It often transpires that the data are scattered. It can happen that the data from one branch is much older than the data from another branch, which makes taking a joint decision for the entire organization impossible. It may also be the case that the data from several sources is redundant, which leads to the situation where a manager is overwhelmed with data from among which it is hard to select the really important information. The organization can then quickly experience the so-called domino effect. Excess data complicate its analysis, and this less effective analysis affects the formation of available options to choose from. On the basis of incorrectly analyzed, incomplete or simply incorrect information, predicting the consequences of a choice is difficult, to say the least. In such circumstances, an option that appears to be optimal is not so in reality [2].

Paradoxically, in this day and age when a great deal of work has been computerized, decision-making is not easier than it was in the past.

In most organizations, including IT organizations, the decision-making process is accompanied by a number of problems [3]:

- excess or insufficiency of data,
- inability to interpret data and transform it into information,
- inaccuracies of data (information),
- dispersed data,
- free access to data,
- difficulties with the aggregation of data and information,
- difficulties associated with reducing uncertainty.

There are IT technologies that support the decision-making process [4]. This support involves solving or simplifying the problems that occur in the process. They allow faster data access, aggregation and analysis. A huge amount of dispersed information from different parts of the company can be aggregated in one place, while maintaining its readability and giving it an ordered structure. These technologies also allow for the analysis of the information and for the creation of reports, thanks to which the issue of uncertainty in the decision-making process is minimized. Thus, the risk of making a bad decision is reduced, and the probability of making the right one is increased. The tools we are referring to here are defined as Business Intelligence.

The implementation of a Business Intelligence technology is a significant cost to the organization. The question is whether the cost can be justified in a quantitative manner? Is it possible to assess the effects of this decision after a system of this class is introduced? Our experience shows that this is a problem for many organizations. The assessment of the situation after the implementation of the system is usually of a qualitative nature and, as it is based on the subjective feelings of the users, can be radically different depending on their position, on the scope of their operations and on the changes which affected them directly [5].

Having obtained very detailed quantitative data collected in the organization prior to and after the implementation of a Business Intelligence system, the authors analyzed the data and established that it is the basis for the construction of an evaluation model to assess the validity of this implementation. This article thus presents a test organization, the indicators developed for measuring key aspects of the business and presents a method for the quantitative evaluation of the effectiveness of such an implementation.

## 2 Business Intelligence as a method for supporting the decision-making process

Business Intelligence, also referred to as BI, is a term, which can be defined in many ways. This paper follows the definition developed by Gartner – a consulting firm specializing in the strategic use of technology [6]. Gartner defines BI as "is an umbrella term that includes the applications, infrastructure and tools, and best practices that enable access to and analysis of information to improve and optimize decisions and performance" [7].

A typical BI system architecture is composed of several elements. The heart of this system is formed by data warehouses, namely databases focused on dealing with analytical queries. Data are transferred to warehouses from several sources: systems such as ERP, CRM, SCM, Call Centers and others, with the help of ETL processes (ETL stands for Extract, Transform, Load) [8]. These processes integrate data from various systems into a single unified model, the so-called multidimensional model. Then, data from warehouses are often used in analytical query processing engines (OLAP, Online Analytical Processing), which allow for quick analyses at different levels and with different sets of questions, sometimes quite abstract ones.

The user can then access the results of these analyses via business and analytical tools. These tools present information as a series of reports and analyses – very often this is achieved via the so-called managerial dashboards. Of course, these applications can provide information in other forms, such as spreadsheets or PDF documents. It is often possible to deliver reports to the mailboxes of selected users, whether as part of the normal course of monitoring, or in the event of an emergency. Typically, BI systems work on online platforms, allowing business users to access reports and analyses through a web browser. The aim is to facilitate access to information regardless of the location of the person who is trying to obtain it. Therefore, the BI system consists of data sources which, due to the presence of ETL processes, enter the data warehouses and go further to analytical and reporting applications. Schematically, the idea of BI can be illustrated as in Figure 1.

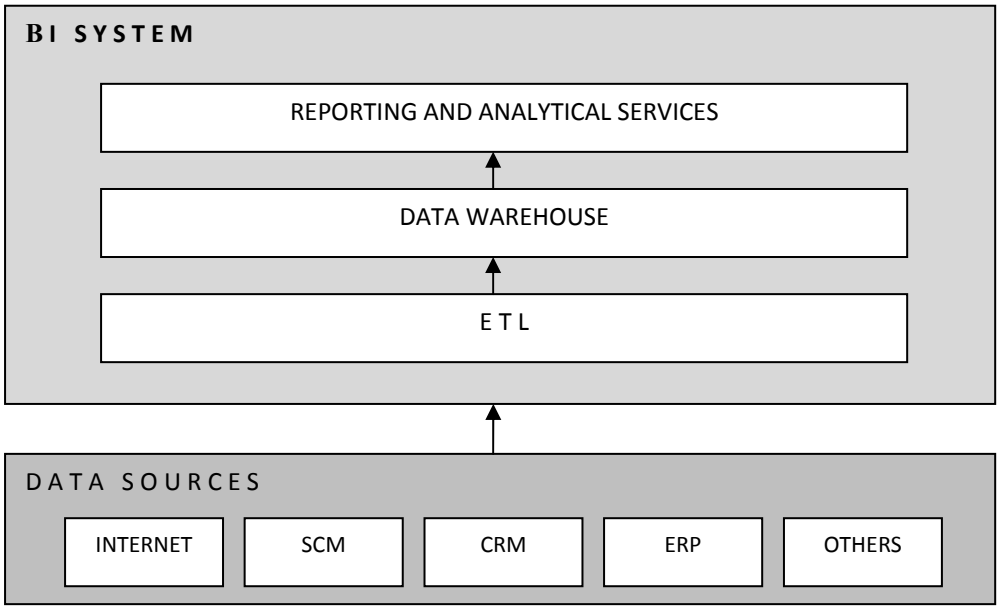


Figure 1. A simplified diagram of the BI system

The BI system helps in decision-making because it interferes in all stages of the process and simplifies them [9]. It stores data in one place (eliminating the problem of open access to data and its dispersion, as well as the existence of duplicates). It solves the problem of outdated information, enables a more accurate data analysis and data conversion into information. It is obvious that only a system that contains all the basic building blocks, listed in Figure 2, can actually support the decision-making process. Full and comprehensive BI systems are offered by corporations such as Microsoft, Oracle, IBM or SAP. The comprehensiveness of the systems offered by these companies is accompanied by a high price. Most small and medium-sized businesses have neither the resources nor the need for such expensive solutions. Nonetheless, it is possible to build a functional BI system, however small, out of components offered by smaller companies, to assist the decision-making process. Such a system, integrating the solution of several different suppliers, was used in the studied IT support organization.

## 3 The characteristics of the studied company and its main problems

The studied entity is a company called Avena Technologies, operating in the IT and telecommunications industries. It is involved in the construction and administration of the urban network in Darłowo (Poland) and it provides services to over 3000 customers. The company provides IT outsourcing services: the installation and administration of network infrastructure, the implementation and administration of VoIP telephony and a helpdesk. In addition, Avena assembles and maintains a wireless Internet service in Gdansk and Gdynia using Hot Spots. Moreover, the company is currently working on an intelligent traffic monitoring system. The project involves the installation of cameras along the Tri-city ring road, the preparation of appropriate software, which allows constant monitoring of traffic on the roads, and in particular, events such as traffic jams, accidents and road works, in order to make this information available round the clock for all Internet users.

Avena was founded 10 years ago, in 2003, and has since been developing dynamically. Currently, it has two offices in Poland, in Gdynia and Gdansk. The company provides external IT services to more than 30 companies in the Tri-city area. The majority of its employees in both locations work in the helpdesk department. Their remote technical support is innovative, and very few companies in Poland provide such a service, hence demand greatly exceeds supply (19 companies in Poland provide IT helpdesk services, none of which is located in the Tri-city) [10]. It was due to the significant workload in the helpdesk department that the company was forced to improve management. With thousands of service requests (SRs in short, this abbreviation will be used later in the paper), the company gradually lost the ability to control its own activities. It became impossible to manage customer data, monitor employee performance, analyze

information and combine it in certain patterns. Moreover, the company had a problem with assessing the quantity of services and the management was not able to determine how much time was spent on customer service, how much it cost, and thus, whether cooperation with customers was remunerative.

Since 2010, when the company started providing helpdesk services, the management's ability to make rational decisions decreased significantly. Due to the nature of the services and the large number of requests, numerous problems appeared preventing or at least hindering the decision-making process. They included:

- excess of data in some areas (e.g. thousands of records related to SRs) and shortage of data in other areas (e.g. knowledge of the current state of the customer IT infrastructure),
- difficult and slow access to data (e.g. a customer makes an inquiry about the possibility of installing a newer operating system on all of their computers – a manual check of hundreds of computers is very time consuming),
- scattered data (over hundreds of computers among dozens of clients),
- inaccuracies of data (without automatic updates on the state of the infrastructure, data must be obtained a new every time),
- inability to monitor own activities (which employees provided services to a given client, how long it took, how to measure their performance),
- problems with the aggregation of data and its transformation into specific information (e.g. due to clients using different hardware and software).

Decision-making in such conditions was associated with working in a state of high uncertainty, regardless of whether the problem existed on the side of the client or the support organization. The management realized that the company is not able to function effectively without the support of appropriate IT systems. To cope with the above-mentioned problems, the company decided to implement a BI system. This was done, however, without the conviction that the decision was in fact the correct one. The management had no premise to justify the planned expenditure. Moreover, the changes that took place in the organization after the deployment of the system were not evaluated. This task became the target of our research. The next chapter presents a method, which the authors have developed to determine the validity of implementing BI in Avena.

## 4 Measuring the effects of implementing the BI system

### 4.1 Assumptions and key performance indicators

Is it possible to measure the effects of implementing BI? For this purpose, it is necessary to create a number of evaluation indicators and then establish the changes in their values before and after the implementation of the BI system, preferably in similar periods of time. The scope of these indicators should cover the most part of the company's operation, not just one particular area. This is due to the fact that the BI system is meant to generally support decision-making in all aspects of business, and thus the indicators are designed to illustrate numerically as many of these aspects as possible.

Although companies are different, several indicators may be used for most of them. Of course, they can be closely matched to the characteristics of the studied organization, and some may arise precisely tailored to the specific organization. Examples of indicators include [11]:

- number of clients served/transactions executed/sales of goods, etc.,
- number and productivity of employees,
- actual working time of employees,
- task initiation-to-completion time,
- degree of customer satisfaction.

It should be noted that some of these indicators can be easily quantified (e.g. the number of transactions), while others are qualitative (e.g. customer satisfaction). The authors, however, set themselves a goal to make a quantitative evaluation. Therefore, it was necessary to use certain simplifications to determine the value of indicators for the evaluation. Naturally, it was also necessary to collect relevant data for comparing the periods before and after the implementation of the BI system. This was obviously much easier to do in reference to the period "after implementation" because the BI system allows the necessary information to be obtained.

To assess the validity of implementing BI at Avena, two periods were compared:

- the period between April 1, 2011 and September 30,2011 (P1),
- and a year later, namely the period between April 1, 2012 and September 30, 2012 (P2).

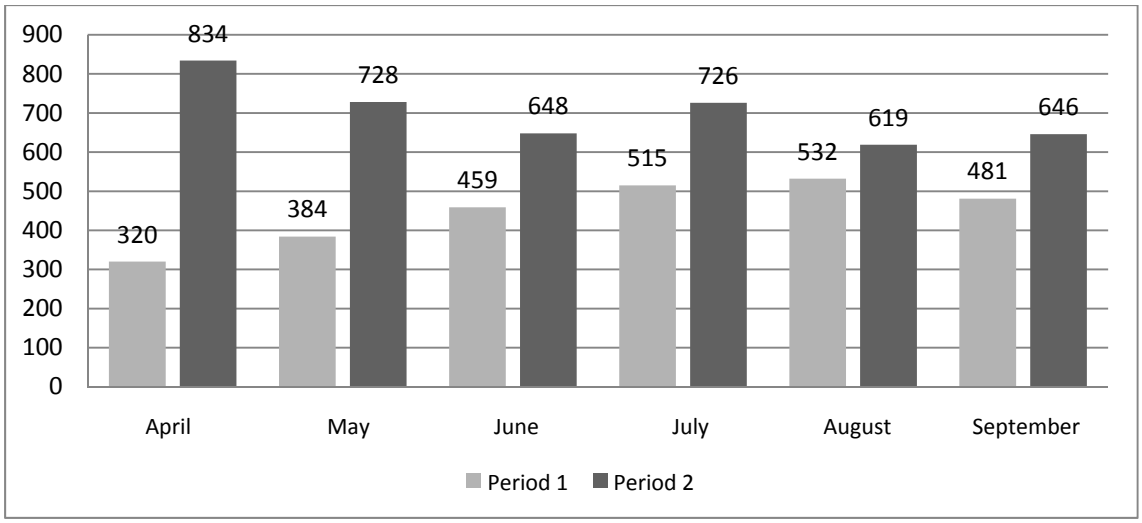


Figure 2. Number of SRs in P1 and P2

To describe the business, the following four aspects were selected:

- the number of SRs (*Service Requests* – understood as problems reported by users to an IT support organization), which require certain actions,
- the number of administrators and their effectiveness,
- mean time to repair (*MTTR* – the average time required to repair a damaged device; in this case, it is the estimated time in which the administrator is required to deal with a request from its opening to closure),
- the degree of customer satisfaction.

In the study, each of these aspects was described quantitatively and one or two indicators were developed for each aspect. It should be noted that the BI system was first launched in late March 2011, just before the start of P1.

### 4.2 Comparison of the number of service requests (SRs)

Within 6 months of P2, the organization processed 4201 SRs in total, which makes an average of 700 requests per month. There were 130 working days between April 1 and September 30, 2012, which gives a little more than 32 requests per day

$$\mathrm{AVG}\frac{\mathrm{SR}}{\mathrm{DAY}} = \frac{4201}{130} = 32.32$$

Within P1, Avena processed fewer requests than in P2 – the number of completed SRs was 2691. There were 131 working days in period 1, which allows the calculation of the average daily number of requests

$$\mathrm{AVG}\frac{\mathrm{SR}}{\mathrm{DAY}} = \frac{2691}{131} = 20.54$$

This number of requests means that during P2, Avena handled far more SRs than the year before – making an increase of 56.11%

$$\frac{P2}{P1} * 100\% = \frac{4201}{2691} * 100\% = 156.11\%$$

Of course, the number of requests, and thus – the average number of requests – it is not the only difference between the study periods. One quantitative value within the 6-month period is not yet conclusive. What is much more interesting is the distribution of the number of requests in given months, which is illustrated below in Figure 2.

As the chart presents, there is a significant difference between the values obtained in the month of April. During the first month after the implementation of the BI system, the studied organization processed less than half the amount of SRs than a year later. In the following months, this difference began to diminish. In August, it was relatively small and amounted to only 16.35%. It is clearly visible that the company needed time to get used to the new system, although this certainly is not the only reason. Agent programs, used to operate the whole system and specifically for data collection, had to be installed on the computers of clients, which obviously took time. Similarly, the customers had to get used to the new request system. After a few months, the differences between P1 and P2 decreased significantly.

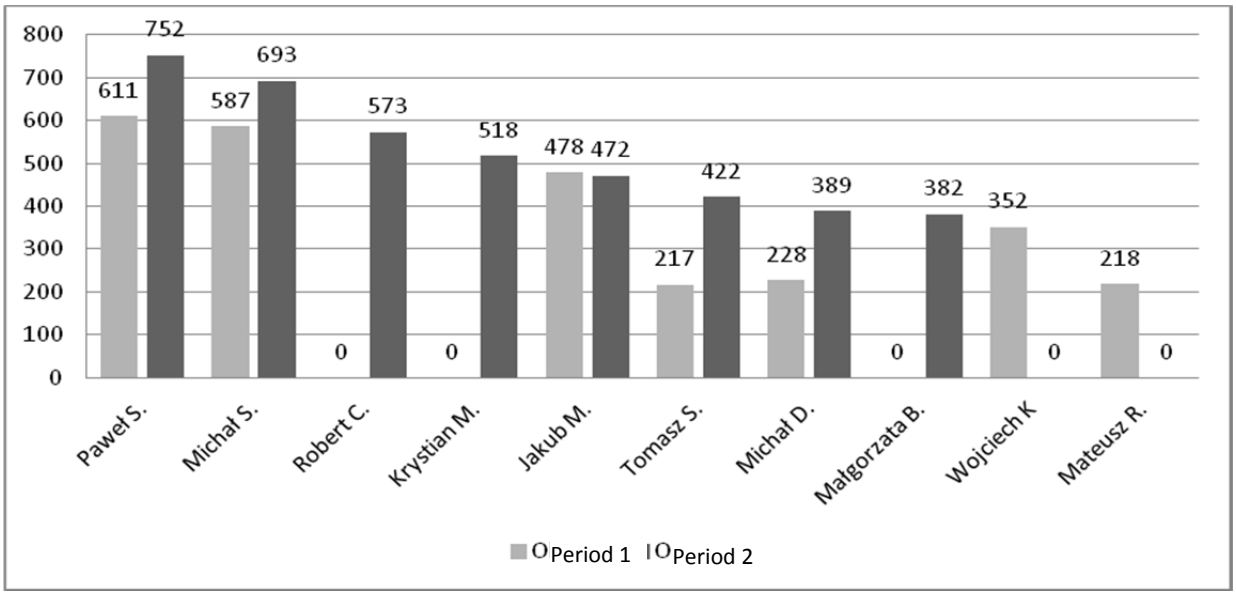


Figure 3. Comparison of the number of SRs closed by administrators

### 4.3 Comparison of the number of administrators and their performance

At the beginning of 2011, seven administrators were assigned to operate the SRs, which is one less than the following year. Five of the groups continue to work for the company. By April 2012, three new administrators were employed. Wherever possible, the number of SRs was compiled on the basis of both periods; in other cases, the amount of an administrator's SRs was shown in one period. The number of SRs closed by administrators in both periods is shown in Figure 3.

The graph shows that in four out of five cases, the administrators who stayed in the company responded to more calls in 2012 than the year before. In one case, the situation is the reverse, but the difference is insignificant (only six SRs, which corresponds to about a day of work). Naturally, one period cannot be compared with the other only on the basis of the five employees who continue working, and a wider view is needed. For this purpose, the average activity time (the actual recorded working time) for all employees in both periods was measured. The value was obtained by dividing the total time spent on tasks (the BI system stores such data) by the number of man-hours available during these periods. The results are shown in Table 1.

Table 1. Comparison of the average working times

| | Period 1 (P1) | | Period 2 (P2) | | |
|---|---|---|---|---|---|
| Administrator | Task duration time (h:m) | Average daily working time (h) | Task duration time (h:m) | Average daily working time (h) | Difference P2-P1 |
| Paweł S. | 651 | 4.97 | 794:00 | 6.11 | 1.14 |
| Michał S | 678 | 5.18 | 728:00 | 5.60 | 0.42 |
| Robert C. | – | – | 414:45 | 3.19 | 3.19 |
| Krystian M. | – | – | 877:45 | 6.75 | 6.75 |
| Jakub M. | 569 | 4.34 | 749:30 | 5.77 | 1.43 |
| Tomasz S. | 472:30 | 3.61 | 312:45 | 2.41 | -1.2 |
| Michał D. | 602 | 4.60 | 738:30 | 5.68 | 1.08 |
| Małgorzata B. | – | – | 479:15 | 3.69 | 3.69 |
| Wojciech K. | 341 | 2.60 | – | – | -2.6 |
| Mateusz R. | 267:45 | 2.04 | – | – | -2.04 |
| | | 3.9 | | 4.9 | |

Table 2. Performance indicator ΔSR – Δ*t*

| Admin. | Avr. *t.* P1 (h) | Avr. *t.* P2 (h) | Δ*t* | SR P1 | SR P2 | ΔSR | Performance Δ SR – Δ*t* |
|---|---|---|---|---|---|---|---|
| Paweł S. | 4.97 | 6.11 | 22.94% | 611 | 752 | 23.08% | 0.14% |
| Michał S. | 5.18 | 5.60 | 8.11% | 587 | 693 | 18.06% | 9.95% |
| Jakub M. | 4.34 | 5.77 | 32.95% | 478 | 472 | -1.26% | -34.20% |
| Tomasz S. | 3.61 | 2.41 | -33.24% | 217 | 422 | 94.47% | 127.71% |
| Michał D. | 4.60 | 5.68 | 23.48% | 228 | 389 | 70.61% | 47.14% |
| | | | 10.85% | | | 40.99% | 30.15% |

By combining data on the average daily working time during in the two periods, it could be easily determined which employees were improving and which were not. It is also worth noting that in P1, two employees had a particularly low daily working time (a little over 2h per day). In effect, it was these employees who were dismissed. It can thus be concluded that employees spent more time solving problems in P2 than in P1. It is unsurprising, given that the number of SRs increased. Therefore, another table should be added to the analysis, one which compares several indicators simultaneously: the number of closed SRs, the average daily working time, the number of SRs per hour and the increase in these values in percentages. Such a comparison table is only relevant for those employees who worked in both periods.

Table 2 illustrates the changes in employee performance in the two periods. First of all, it compiles the time needed to close the SR and shows whether the administrator worked more or less. The Δ*t* indicator itself does not say, however, whether this is good or bad – after all, an employee may work less and be more efficient. To calculate such performance, the next three columns compare the changes in the number of problems solved (ΔSR). The last and most important column is the indicator of employee efficiency. It summarizes the difference in the time needed to complete a task and the change in the number of closed SRs. This helps to determine the growth in the administrator's performance. If the value in this column is 0, it means that the increase in the average working time is directly proportional to the increase in the number of SRs. If the value is positive, the administrator uses his time efficiently, if negative – less efficiently. The table shows that four-fifths of administrators increased their efficiency a year after the implementation of BI.

### 4.4 The comparison of mean time to repair (MTTR)

The parameter of MTTR is the average time, which is needed to repair the device after failure [12]. This time is often specified in a contract and can determine whether a company dedicated to maintenance (in this case, the studied company meant to address issues related to IT) fulfills its obligations as expected (i.e. the SLA – Service Level Agreement). The same is true in this case – customers expect that their problems will be resolved within the specified time. If such time is not indicated by the SLA, the manager decides what the MTTR is for a particular task while allocating tasks. After the problem is resolved, the request must first be verified and then closed. The average closure time, verification time and MTTR in P1 were studied to establish whether the company met its obligations in the required time. In P2, in four out of six cases the MTTR was exceeded. Table 3 presents the comparison of these values with P1.

As it transpires, in every month within P1, Avena managed to fit into the required task closure and verification time. In April 2011, the company had a significant time margin of over 1100 man-hours. The management realized that a lot of time was wasted and gradually reduced the MTTR. Similarly, clients came to the conclusion that the time they had allocated to such services was overestimated and they reduced it too. Nonetheless, in P1, the MTTR remained too high and the company had an excess of time. In P2, the situation was reversed: the company did not keep up with the work. If Avena signed an SLA in P1, it would have no problems with respecting the provisions of the agreement. In P2 it is impossible.

Table 3. MTTR compared with the closure time and the verification time of SRs in P1

| | Period 1 | | | Period 2 | | |
|---|---|---|---|---|---|---|
| Month | MTTR (h) | Closure time and verification time (h) | Difference | MTTR (h) | Closure time and verification time (h) | Difference |
| April | 1594.8 | 481.25 | 1113.55 | 1320.20 | 1010.05 | 310.15 |
| May | 1407.2 | 558.75 | 848.45 | 1161.10 | 1188.42 | -27.32 |
| June | 1005.3 | 714.75 | 290.55 | 863.10 | 835.00 | 28.1 |
| July | 775.4 | 585.75 | 189.65 | 868.80 | 1144.25 | -275.45 |
| August | 1394 | 702 | 692 | 756.60 | 1015.75 | -259.15 |
| September | 1144.5 | 627 | 517.5 | 797.90 | 1093.25 | -295.35 |
| | **7321.2** | **3669.5** | **3651.7** | **5767.70** | **6286.72** | **-519.02** |

In a theoretically ideal situation, the MTTR should be equal to or greater than the times of closure and verification. Naturally, the smaller the difference between those times, the more effective the use of working time is. The time required for closure and verification should amount to about 90–95% of the MTTR, so that in the event of an emergency, there would be a certain time margin. Excluding such a time margin, the upper limit may be set at 100% (i.e. the time of closure and verification of SRs is exactly the same as the MTTR). Table 4 shows the value of the quotient of the closure and verification time and the MTTR.

As shown in Table 4, in seven of the researched months the value of the closure time and verification time/MTTR is too low; in four months, it is too high, and only in one it is appropriate (June 2012). The Table is complemented by Figure 4.

Table 4. Indicator of the closure and verification time/MTTR

| | Period 1 | | | Period 2 | | |
|---|---|---|---|---|---|---|
| Month | MTTR (h) | Closure time and verification time (h) | Closure time and verification time/MTTR | MTTR (h) | Closure time and verification time (h) | Closure time and verification time/MTTR |
| April | 1594.8 | 481.25 | 30.18% | 1320.20 | 1010.05 | 76.51% |
| May | 1407.2 | 558.75 | 39.71% | 1161.10 | 1188.42 | 102.35% |
| June | 1005.3 | 714.75 | 71.10% | 863.10 | 835.00 | 96.74% |
| July | 775.4 | 585.75 | 75.54% | 868.80 | 1144.25 | 131.70% |
| August | 1394 | 702 | 50.36% | 756.60 | 1015.75 | 134.25% |
| September | 1144.5 | 627 | 54.78% | 797.90 | 1093.25 | 137.02% |
| | **7321.2** | **3669.5** | **53.61%** | **5767.70** | **6286.72** | **113.10%** |

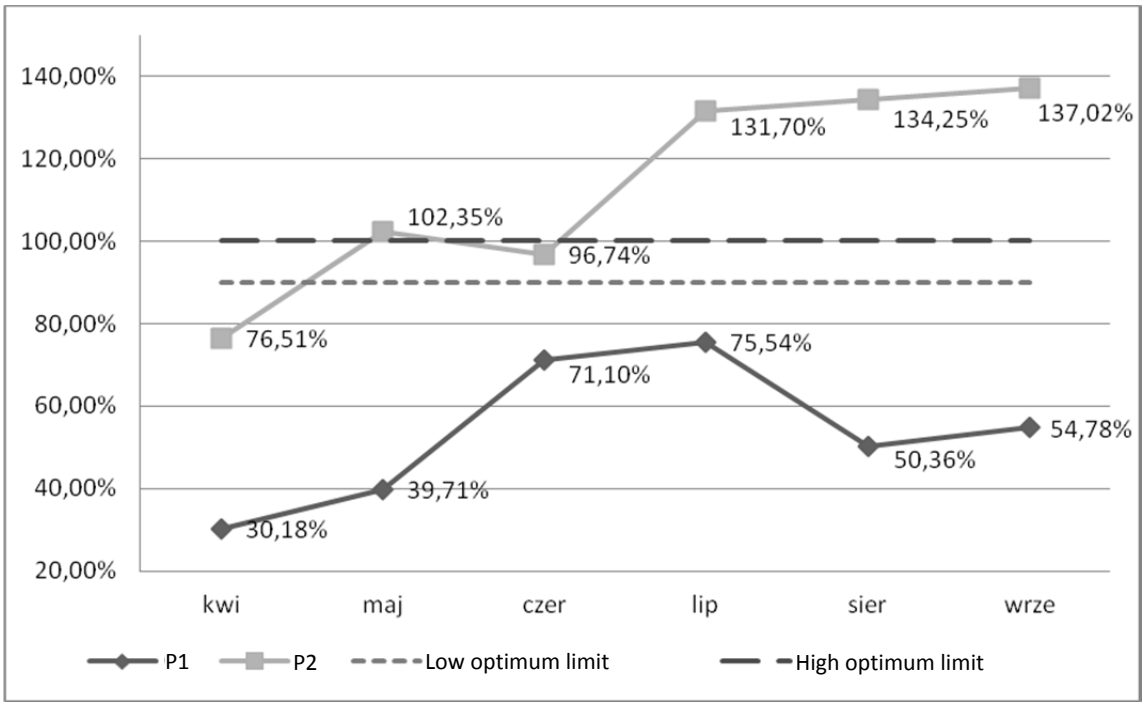


Figure 4. Indicator of the closure and verification time/MTTR in periods P1 and P2

The graph shows clearly how much the values of the closure and verification time/MTTR deviate from the norm. The values of the indicator for both P1 and P2 periods should be between the lower and the upper limit – then the value of the indicator would be optimal. Two trends can be observed in both periods: in P1, the closure and verification time/MTTR was generally too low, and in P2 – it was generally too high.

### 4.5 The comparison of firms to which services were provided and the ratio of open SRs to closed SRs

The increase in the number of SRs in P2 in relation to P1 is not accidental. Between these periods, the company gained new clients, without losing any. In P1, the number of clients was 29, in P2 it was 36. Among the top 10 largest clients, seven of them reported more than 100 requests, others reported fewer. Interestingly, the eight largest clients in P1, remained in P2 in the top 10 most important clients for Avena. It is very important that, despite some shortcomings in the company's operation (which were mentioned before), the clients continued to use the services of Avena (Table 5).

On average, each client-company reported 100% more SRs than in P2 than in P1 (which does not necessarily mean that the total number of requests between P1 and P2 also doubled). Although this value is positive for Avena, the authors indicated to the management the appearance of extremes in specific data. Some companies almost ceased to use the services of Avena (Why? Has the contract expired or are the clients dissatisfied with the services?). It can be said that the change in the number of requests reported by each of the companies is an indicator of satisfaction with the services provided by the researched organization.

Table 5. The change in each clients' open requests

| Open SRs in P1 | Open SRs in P2 | Δ OSRC | |
|---|---|---|---|
| 2691 | 4201 | 100.81% | For all clients |
| 2691 | 3759 | 99.32% | Excluding new clients |

Table 6. Values of the evaluation indicators

| Item | Indicator | Indicator acronym | Type of indicator | Value | Norm/comment |
|---|---|---|---|---|---|
| 1 | Change in the number of SRs | ΔSR | Direction | + | No higher limit |
| 2 | Change in the average daily working time of an administrator | ΔAAT | Direction | + 1 h | No higher limit |
| 3 | Value of the average daily working time of an administrator | AAT | Value | 4.9 h | 0–8 |
| 4 | Performance of the administrators who worked in both periods | Δ SR - Δ t | Direction | + 30.15% | No higher limit |
| 5 | Value of the ratio between the closure time and verification time and the MTTR | Closure time and verification time/MTTR | Value | 113.10% | 90–100% |
| 6 | Change in the number of clients | ΔClient | Direction | + 24.13% | No higher limit |
| 7 | Change in the difference between open and closed requests | ΔO - ΔC | Value | -19 | 0 |
| 8 | Client retention | %SRC | Value | 45% | 75–100% |

According to a normal schedule, if company X reported a number *n* of SRs in one period, in the same period in the following year it should report roughly the same *n* amount (this assumption does not take into account significant changes that may occur in the company – a significant drop in value, mass layoffs, the construction of new premises and the employment of new workers, etc., which could obviously significantly affect the number of requests). Naturally, the increase or decrease in the number of requests may depend on random events. The likelihood of such events is, unfortunately, impossible to estimate, although it can be assumed that there is the same chance for a random occurrence of both negative and positive events. Therefore, the impact of random events was omitted from this analysis.

## 5 The evaluation of the performance of the BI system implementation

The interviews conducted by the authors show that at some stage of the company's development, the management of Avena was no longer able to make the right decisions. That is why in early 2011 BI was implemented. Between the study periods, the organization changed under the influence of actions resulting from the conclusions drawn from the data collected and analyzed by the BI system (at least in part). Although the various individual decisions are unknown, their impact can be measured by several parameters. Thanks to the prepared indicators (described earlier), it can be evaluated whether the implementation of the BI system was justified and if, on the basis of the obtained information, the company made decisions that increased its efficiency.

The authors chose eight indicators, which belong to either one of these two categories:

- *Direction indicators* – They indicate the direction of the changes, which take place, their greatest significance is not their value but their symbol.
- *Value indicators* – In their case what matters most is the number itself, which should fit within a certain range. The range was designated subjectively by the authors.

All the indicators have been compiled in Table 6, including the calculated values and suggested norms for each of them. It is important to briefly comment on and justify the value of each of the indicators, assessing its nature (positive/negative).

Each value has been evaluated by the authors on a scale of 1–5. A brief explanation as to why the indicator received such an evaluation is presented in the column "comments". The evaluation of the BI system implementation and of the effects of actions undertaken by Avena will take the form of an arithmetic mean of the individual indicators.

Finally, the effectiveness of the change that Avena underwent has been evaluated at 72.6%. The following evaluation brackets have been assumed (in percentages):

- <0.50> ⇨unsatisfactory
  values below 50% mean that the changes do not bring any positive effects, not even small ones,
- (50.65) ⇨ satisfactory
  the changes are small but positive,
- <65.80) ⇨ good
  the changes are rather positive, although not all the solutions are adequately developed,
- <80.100> ⇨ very good
  the changes are clearly positive, few elements require improvement.

Based on this scale, it can be stated that the result of 72.6% is good enough to say that the implementation of the BI system was profitable. At the same time, it was made evident which areas of the company's operation are not working efficiently enough. On the basis of analyses and comparisons, as well as the authors' knowledge about the company, a few appropriate and inappropriate decisions taken by the management can be pointed out. It is also possible to indicate some appropriate decisions, which were made for good reasons and which turned out to be not quite right due to changes in certain factors:

- It was possible to determine which employees worked ineffectively. They were dismissed and replaced by others who work more effectively.
  ⇨ The right decision.
- Thanks to grouping incidents, it was possible to define certain recurrent problems. The company introduced the so-called SIP policy. If a problem recurs, an employee (usually from the management) is asked to create an SIP, namely an article that ends up in the knowledge base and that describes step-by-step how to solve the problem. In effect, the performance of employees increases and a greater number of requests can be processed by an administrator.
  ⇨ The right decision.
- The MTTR was reduced. It was discovered that the MTTR in P1 was underestimated, which meant that employees had too much time to complete a task; thus, the expected closure and verification time of SRs was reduced. Because employees had an excess of time, it was possible to sign contracts with a greater number of clients, which was to help use the working time more effectively.
  Unfortunately, the current clients also concluded that the problems they addressed to Avena can be resolved quicker and they too reduced the MTTR. In result, Avena provides services to too many clients with respect to its capabilities and it exceeds the MTTR. The decision to reduce the MTTR was, therefore, right in P1; however, due to the change in external factors, it brings negative results in P2.
  ⇨ The decision was right to a degree.

In conclusion, it can be stated that the evaluation of the effectiveness of the BI system implementation at 72% is justified. Thanks to this investment, the company managed to detect some problems and, by taking decisions based on specific information, respond to them. It is clear that the company has developed significantly since the beginning of the implementation process in P1 until the end of P2. However, the rapid development brought new problems, which the company must now face. Avena is not yet able to use the full capacity of the system, which it possesses – the management overlooked a few cases in which a problem should have been detected and dealt with – for example, the employment of one or two administrators could have solved the problem of exceeding the MTTR and would have thus reduced customer dissatisfaction. Nonetheless, despite some imperfections in the functioning of the organization, the decisions taken by the management of Avena proved to be accurate in most cases.

It should be noted that the evaluation of the decision to implement the BI system was based on the assumption that other than the implementation of the BI system, nothing else changed in the studied organization. Naturally, this assumption is not entirely correct as every organization changes over time.

Table 7. Indicator value evaluation

| Indicator | Comment | Evaluation |
|---|---|---|
| ΔSR | A 56% increase in the number of requests in a year signifies the great pace of the company's development | 5 |
| ΔAAT | A 1-h (or 25.64%) increase signifies that the administrators indeed work 1h longer a day.<br>It is a change in a good direction, provided that the AAT is not exceeded | 5 |
| AAT | The average daily working time of the administrators is 4.9 h.<br>Assuming that a working day is 8-h long, 4.9 h makes only 61.25% of a working day.<br>The value of the indicator is much too low; the administrators do not use their working time in full | 2 |
| Δ SR - Δ t | The value of the Δ SR - Δ *t* indicator at 30.15% signifies that the administrators who worked in the company in P1 and P2 disproportionately increased their performance by 30% when compared with the expected value.<br>This is a lot | 5 |
| Closure time and verification time/MTTR | The value of the closure time and verification time/MTTR indicator at 113.10% signifies that the company does not fit into the designated SR times.<br>On the other hand, the MTTR was evidently underestimated in P1.<br>Adjusting the MTTR is a positive change, however, not with such a number of SRs.<br>Avena is not capable of keeping the rigorous MTTR defined in the SLA | 2 |
| ΔClient | With only one additional employee, Avena managed to provide services to 24.13% more clients in P2 than P1.<br>This is a significant increase | 5 |
| ΔO - ΔC | In P2, the company closed 19 requests more than it opened which means that it was forced to close and verify overdue requests.<br>On the other hand, the value of 38 in P1 meant that work was done too slowly and the tasks were spread over too much time.<br>The direction of the changes is positive but the value of the indicator continues to be incorrect | 3 |
| %SRC | More than half (55%) of clients delivered less requests in P2 than in P1.<br>This could result from the clients' situation or the level of the service provided.<br>Although most companies use Avena's services to a smaller degree, no client ceased cooperation.<br>It is necessary to study the extremes and establish the causes of the present phenomenon | 2 |
| | | Evaluation: 3.63 (72.6%) |

The analyses were based entirely on the specific numerical values from the corresponding tables of the database. However, not everything that changes in a company is recorded in those tables. For example, the increase in an employee's efficiency is partly the result of the introduced methods, and partly due to the person's increased experience.

The same could be said of other indicators. Unfortunately, it is impossible to quantitatively evaluate the impact of factors, which are intrinsically irrational. For this reason, it was assumed that only data that can be expressed in numbers would be taken into account, and that any changes in the company result from the implementation of the BI system. With this assumption in mind, it can be stated that the application of the BI system led to the reduction of problems associated with decision-making and resulted in an improvement in this area, which positively affected the work of the entire organization.

## 6 Summary

This paper presents a method for evaluating the implementation of information technology called a Business Intelligence system in an IT organization. Due to expanding the scope of its business, the studied organization of IT support faced a number of new problems, which it was unable to cope with without the help of an IT system. The system was implemented, yet without any prior analyses of the potential effects of such change.

The authors carried out such analyses by comparing data available for two periods of time. This gave the opportunity to determine in which aspects of its operation the company gained and in which it lost. It transpired that the company's undoubted success was the increase in the number of processed SRs by more than half, and increasing employee productivity by 20–30% via observations, standardization and the creation of knowledge bases. Avena now provides services to 24% more clients than before.

These improvements are the result of appropriate decision-making, which has been made possible through the use of Business Intelligence tools. A few risks were noticed: exceeding the accepted MTTR or establishing cooperation with too many clients with respect to the company's potential.

It should be noted that the evaluation of the decision to implement the BI system was based on the assumption that apart from the implementation of the BI system, nothing else changed in the company. Naturally, this assumption is not entirely correct as every organization changes over time.

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The authors' current goal is to verify the model for other support organizations, and for technologies other than Business Intelligence .

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# CLOUD COMPUTING AS A TOOL FOR IMPROVING BUSINESS COMPETITIVENESS

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***Abstract:*** This article organizes knowledge on cloud computing presenting the classification of deployment models, characteristics and service models. The author, looking at the problem from the entrepreneur's perspective, draws attention to the differences in the benefits depending on the cloud computing deployment models and considers an effective way of selection of cloud computing services according to the specificity of organization. Within this work, a thesis statement was considered that in economic terms the cloud computing is not always the best solution for your organization. This raises the question, "What kind of tools should be used to estimate the usefulness of the model cloud computing services in the enterprise?"

***Keywords:*** cloud computing, data processing, opportunities, threats, service models, deployment models, the characteristics of cloud computing, innovation, estimating operating costs.

## 1 Introduction

One of the most important resources in the modern economy is information. Organizations depend on how fastly the data are accessed as the finished product, which is useful for decision making at all levels of management: strategic, tactical and operational level. At the same time, one of the problems of any organization is an excess of data. To effectively use the data, they must be collected, stored and processed with the support of tools such as: databases, data warehouses and BI systems. These tools allow fast access to data and present them in a transparent manner, which facilitates the work of, among others, managers.

Such a method of data processing requires an appropriate infrastructure. To begin with, special rooms designed for server rooms to the servers, disk arrays, backup copy systems, ending with the client stations should be maintained. All elements of the network generate costs for the organization at the time of purchase, during use and at a time when no longer useful. Software licenses also increase costs associated with the IT sector. Some organizations, especially small, are not able to meet these costs losing the opportunity to effective competition in the marketplace.

A remedy for the high costs of collecting and processing data within the organization may be to build virtual servers in the environment of cloud computing. There are companies that offer the opportunity to make use of hardware resources, operating platforms and software as a paid service via the Internet. The recipient is obliged to cover only the costs of purchase and maintenance of terminal stations, the Internet, cloud computing service costs and maintaining a minimum IT level dependent on the size and needs of the organization.

Looking at the phenomenon of cloud computing from the entrepreneur's perspective purchasing cloud computing service, a question arises whether this service should replace the collection and processing of data within the organization? What are the opportunities and risks, benefits and obligations coming out of the change of data processing?

This article presents the current state of knowledge on the concept of cloud computing and identifies questions that companies need to answer considering how to process the data within its own structure. Contrary to popular opinion, presented in literature and during conference speeches, the author believes that the current level of development of the cloud computing service cannot, in any case, be an alternative to the existing centers in the organizations. From the point of view of the entrepreneur, the most important indicator in choosing the method of data processing is the level of costs. Poorly chosen cloud computing service may result in increased costs, which negatively affect the competitiveness of the company.

## 2 Cloud Computing

### 2.1 Definitions

Cloud computing idea is not new. The concept of cloud computing is that IT resources, both hardware and software, are treated by the user as another medium such as electricity, gas or water. The recipient does not physically wonders where electricity comes from in his

socket, just pays for the service. Most of us use cloud computing without being aware of it. A perfect example is the cloud computing e-mail service. The majority of users do not know where physically located e-mail messages are. Using the mailbox is done over the Internet, regardless of the location or device you are using; you always have access to e-mails. Therefore, the mail system supplier provides for us a service. The very concept of cloud computing has been used for the first time by Net Centricin 1997, so it is relatively new and still evolving, making it difficult to find one recognized by all definition in the literature.

According to IBM, cloud computing is a new model of IT use and processing style in which the business processes, applications, data and IT resources are delivered to users in the form of services [5, p. 145]. Another definition comes from the portal Wikipedia: Cloud computing is a processing model based on the use of services provided by external organizations. Functionality is understood as a service (which gives added value to the user) offered by the software (and the necessary infrastructure) [15]. The accepted definition of cloud computing in the scientific studies is that one developed by the National Institute of Standards and Technology (NIST) in 2011. According to the NIST, cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model is composed of five essential characteristics, three service models and four deployment models [10, p. 3].

All definitions consequently maintain that the object services are broadly defined IT resources. However, only the NIST definition emphasizes the factor that distinguishes cloud computing from other forms of outsourcing. It refers to the statement that the service is available on-demand, without necessary earlier orders or starting fee as it take place, for example, in the co-location model. Another important feature is the method of calculating fees. In contrast to classic forms of IT outsourcing, a cloud computing model provides a different solution where we pay for the resources actually used, and not for their declared use.

Looking at cloud computing from a purely technical point of view, this service is a blend of the known solutions in the provision of IT services, for example:

- *Utility computing* has usually envisioned some form of virtualization so that the amount of storage or computing power is available to individual business units or procedures. It also allows thorough settlement of the amount of processed data [13].
- *Grid computing* is defined as a hardware and software infrastructure that provides dependable, consistent, easily customizable and affordable access to computing resources [1, pp. 749 – 771]. In contrast to utility, computing can also use the computing power of PC.
- *Outsourcing* is the transfer to external service providers in accordance with the provisions in the agreement (contract) repeated internal tasks of an organization related to the implementation of staff, equipment, facilities, equipment, technology and other resources and decision-making powers regarding their use [3, p. 3].
- *Virtualization* is characterized by abstract perception of hardware resources so that the resource can be activated to operate in various ways, regardless of its physical form or location [9, p. 856]. This allows more efficient use of existing hardware environment resources by modifying the characteristics of any resources, adapting them to user requirements.
- *Distributed computing* term conceals the technique of running calculations, enabling the sharing of computing resources such as: private computers, servers, etc., which is usually geographically dispersed. In a general sense, this technology means the data processing regarded as a public service. In other words, the client does not matter where the data are stored or which computer does the job. The customer can order the information or the calculations and results in the scope and time required [4, p. 37].

The functionality of these concepts allows for innovation within the model of business management. The availability of IT resources on demand and bearing the charges for the actually used resources allows you to change the cost structure of the organization. It leads to the reduction of the group cost classified as capital expenditures (CAPEX)[1] and increasing of operating

[1] CAPEX- expenditures allocated to buy fixed assets such as equipment, e.g. IT equipment.

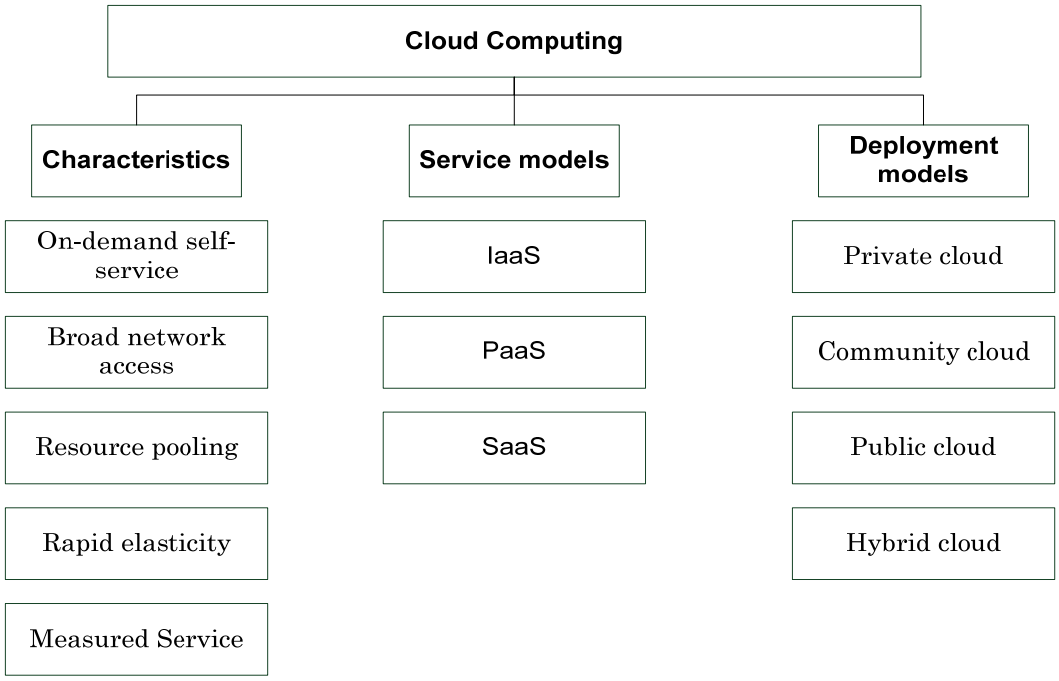


Figure 1. Concept of cloud computing services
(*source: own elaboration*)

expenditures (OPEX).[2] This means that the barrier related to the purchase of IT infrastructure or the necessary high costs of the rent in advance ceases to exist.

A company using the cloud computing model bears the charges on an ongoing basis, as part of the operating costs.

The basic premise of the cloud computing is the availability of services delivered over the Internet or intranet, based on a model composed of five essential characteristics, three service models and four deployment models shown in Figure 1.

Organizations taking the decision to use cloud computing services do not reflect that kind of cloud is to let suitable. This leads to inefficient use of IT, and in extreme cases, to increase in the operating costs of those departments. To avoid such situations, we must understand the advantages and disadvantages of the different types of clouds. For this purpose, the elements shown in Figure 1 will be discussed in more detail.

## 2.2 Essential Characteristics

- *On-demand self-service* - a consumer can unilaterally configure provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider.
- *Broad network access* - capabilities are available over the network and accessed through standard mechanisms that promote use by heterogeneous thin[3] or thick client[4] platforms (e.g. mobile phones, tablets, laptops and workstations).
- *Resource pooling* - the provider's computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand.
- *Rapid elasticity* - capabilities can be elastically provisioned and released, in some cases automatically, to scale rapidly outward and inward commensurate with demand.

[2] OPEX – is the sum of a business's operating expenses for a period of time.

[3] Thin client is a computer or specialized device (computer terminal) and related software client, enabling support for applications created in the client–server architecture. A thin client occurs as independent of the supported application server (the change does not involve having to change client software). Another advantage is the low demand for processing power [15].

[4] Thick client is a computer in client–server architecture or networks. It refers to the user's workstation, which is equipped with a set of peripherals, operating system installed and set of applications. Programs are executed directly and autonomously at the station does data processing and data exchange with the user and other computers on the network. Data are stored on the server side. [15]

*Measured service* - cloud systems automatically control and optimize resource use by leveraging a metering capability at some level of abstraction appropriate to the type of service (e.g. storage, processing, bandwidth, computing power, RAM and active user accounts). It provides transparency for both the provider and consumer because of the pay-per-use structure.

The author refers to the definitions of the characteristics recommended by the National Institute of Standards and Technology [9, p. 2]. These characteristics are the pillars of what is called cloud computing. The resignation of one element will affect the whole cloud computing model. The first four characteristics are responsible for the flexibility of the solution in terms of the availability of IT resources. Measured service allows charging customers according to usage.

### 2.3 Service Models

Software as a service (SaaS) is defined as the capability provided to the consumer to use the provider's applications. Recipient decides which package of programs offered by the supplier will serve his needs. The SaaS model allows entrepreneurs to pay only for the software features they actually run and charge for actual time of use. The software package dedicated to the individual customer operates, maintaining an adequate level of data security, in addition to other software packages on a shared server. The client shall determine the number of employees who have access to the shared programs. The number of employees and the actual usage are the basis for calculating the subscription fee. Software as a Service removes the need to handle the installation, set-up and often daily up keep; reduces cost of implementation of new software; gives an advantage of speed implementation and access to the latest software. Because the software is hosted remotely, users do not need to invest in additional hardware and purchasing software licenses.

Platform as a service (PaaS) is defined as a computing platform being delivered as a service to the customer delivering via the virtual work environment, among others, operating systems such as Windows Azure created by Microsoft or Google's Chrome OS. Customers can use the infrastructure and development tools hosted by a service provider to build their own applications and working environment. This model deploys onto the cloud infrastructure consumer-created or acquired applications without the need to purchase hardware or software installation. PaaS service is available to any user regardless of the used end station. In addition, the client is not involved in the maintenance of the operating system itself, updating, backup, etc. The customer is to only maintain and take care of self-created or installed applications. The advantages of using PaaS services include: no need to purchase a commercial license for operating systems, no need to update operating environments by the service provider, access to the latest versions of operating systems at no additional charge and the possibility of using the work environment on different computers.

Infrastructure as a service (IaaS) is to provide the hardware understood as RAM, disk space, computer performance, etc. over the Internet in the form of virtual resources scaled according to the needs of the recipient. Resources that are the supplier property will be virtually separated within the physical devices under his control. The owner of the operating environment, installed programs and processed data in this service model, is the recipient. This implies a need for maintenance and updating of software. The advantages of using IaaS services removes the hardware purchase costs and maintenance costs of network devices, provides the ability to quickly expand virtual hardware resources (if necessary) and the ability to reduce virtual hardware resources, and the saving of office space determined by the lack of need for a complex server.

Table 1 presents a summary of the described cloud computing services and organizes issues of ownership and responsibility for the individual elements as the subjects of services. Sign (-) indicates that the control of the resource has the customer, sign (+) indicates that the resource is under provider control, while the sign (+/-) indicates that the resource is under common control of both entities.

Table 1 presents the distribution of responsibility for IT infrastructure between the provider and the recipient. In each of the listed cases, the company as a customer bears the responsibility for the data. Responsibility for infrastructure differs, depending on the variant. Customer must reckon with the fact that the greater the responsibility is shifted to the provider, the greater will be the cost of the service.

Table 1. Distribution of control in models of cloud computing services (*source: [6, p. 6]*)

| Specification | Classic model | IaaS | PaaS | SaaS |
|---|---|---|---|---|
| Data | – | - | - | - |
| Applications | - | - | - | + |
| Operating environment | - | - | + | + |
| Virtual machine | - | +/- | + | + |
| Servers | - | + | + | + |
| Data warehouses | - | + | + | + |
| Network | +/- | + | + | + |

### 2.4 Deployment Models

Public Cloud is the most popular and least engaging customer types of cloud computing. The cloud infrastructure is provisioned for open use by the general public. The public users may pay fixed monthly fees for services they utilize. Examples of companies offering this type of service include Google, Microsoft, Amazon and leading Polish groups: Onet.pl Group and ATM SIS.A. There are also free versions of public clouds such as already mentioned mailboxes. Google has gone one-step further and made users of Gmail mailboxes tools to create a network of office documents, Web pages and virtual disks. Another feature of the public cloud, whose presence should be aware of, is the fact that services can be provided by more than one entity, e.g. one company provides virtual hardware, another operating platform, and even other applications used by the customer.

Taking everything into account, Public Cloud is a form of cloud computing, which is the most convenient for the customer. Recipient procures certain services, pays a fee and through Internet connection which is required in this case, starts using the service. Public Cloud combined with IaaS, PaaS and SaaS package services is most beneficial for the company. Using this combination frees the business from having to purchase, service and maintain hardware and to pay for software licenses. It saves office space, electricity and takes advantage of many other benefits that will be presented later in the article.

Why do not all benefit from this kind of technology? There are many existing reasons in the literature but from the business point of view the most important seems to be a concern for safety data processing, especially classified information. Therefore, security consideration may be substantially responsible for the concept of private, common and hybrid clouds.

Private cloud is a solution to the problems of data security in cases where the company does not want or cannot process them outside fully controlled by them data centers. More specifically, Private Cloud solves legal issues. Physical security of data and protection against hacker attacks are a separate issue.

Private cloud infrastructure is operated solely for a single organization whether managed internally or by a third-party and hosted internally or externally. From a technical point of view, the purchase and construction of hardware infrastructure private cloud is not much different from the classic server. The difference lies in the layer of software that runs on the available hardware.

It is easy to notice that this type of solution is not available for any organization. Undertaking a private cloud project requires a significant level and degree of engagement and requires the organization to have sufficient funds and skilled employees, which is unavailable for many companies, such as in the SME. Therefore, these solutions are typically used by large companies where the scale of projects linked to the legal protection of data processed is economically justified.

However, the question is if this type of private enterprise has a chance to actually provide a higher level of security against hackers or natural disasters that can lead to irreversible data loss. For large organizations, such as multinational corporations, where there are adequate financial resources, perhaps it does. In other cases, companies are notable to provide better security than external suppliers.

Cloud computing providers invest in a giant cloud data centers, often costing $ 500 million or more. In 2008, Google spent on the construction of data centers of $ 2.3 billion. Economies of scale are the key factor applied by cloud providers. Huge orders for equipment, energy, as well as strategic location of data centers

around the power plant, data center operators can count on big discounts of 60% and more. An example is Amazon, which in 2008 paid about 90 million dollars for 50 thousand SGIRackable servers. In normal trading, they cost 215 million dollars. [12]

We can likely find out that a single organization is notable to guarantee a higher level of security for their data due to the funds invested by cloud service providers, economies of scale determined by the amount of customers and duplication of data centers in different parts of the country or the world. In addition, there are issues related to the experience of employees in safety and innovation and modernity solutions.

In conclusion, private cloud is technically and costly neighboring the classical data processing. The whole process and the responsibilities and costs remain at the client side. However, private cloud gains more efficient use of network resources (servers, disk arrays, etc.), and retains control of classified data what is important for the current legislation reasons.

Community cloud is defined by NIST as infrastructure provisioned for exclusive use by a specific community of consumers from organizations that have shared concerns (e.g. mission, security requirements, policy and compliance considerations). It may be owned, managed and operated by one or more of the organizations in the community, a third party, or some combination of them, and it may exist on or off premises [10, p. 3]. Thus, community cloud is in a sense a kind of private cloud connecting entities with a similar profile that agree to share technical resources and, in some cases, the data. Organizations that cannot afford to build a private cloud are investing in community cloud, and because the law does not allow for the processing of data centers that are not under control of the company. As the number of participants in such a project is much smaller than in the case of public cloud, part of the economic benefits resulting from economies of scale is not possible to achieve. However, compared with the private cloud construction and maintenance the costs are much lower.

Hybrid cloud is a composition of two or more distinct cloud infrastructures (private or public) where some of the data are processed in the public cloud and the classified data in the private cloud. Hybrid cloud seeks to deliver the advantages of limiting the capacity of private clouds, which allows operating in accordance with the law and potential cost saving which is smaller than the costs of management data of public clouds.

Despite the deployed variant of cloud computing services, the main problem arises from the need for technological standards. This leads to a situation where the client has limited ability to change service provider. This carries a risk of dependence on single supplier companies, who may impose inflated price of the service.

### 2.5 Selection of cloud computing services

The main motive in favor of the deployment of cloud computing solutions in organizations both private and public is economic considerations. Enterprises processing the data in a classical way must themselves take care of all the related aspects of the process such as: security, modernization of IT infrastructure, and software licenses. Cloud computing provides many opportunities for cost savings to companies and individual users. It should be noted, however, that in its current form, the cloud computing is not a perfect solution, and as each new solution has its drawbacks, it eliminates part of the known risks, but also creates new ones.

The authors of the various studies agree that the main advantages of cloud computing include saving, performance, scalability, availability, reliability, time of implementation of new functionality. Launching new Google Apps services at the University of Warsaw is an example of a much faster launch of IT services. Within three months of the service running the UW students were provided with the access to email, storage of documents on the web, creation web pages, blogs and the use of office software package together with the transfer of existing student mailboxes from the university server [14]. The launch of a new multimedia service newspaper Rzeczpospolita may serve as a second example. The site was built entirely in the cloud within three weeks. For comparison, the construction time of the same service in the bar form would take from 6 weeks to 4 months [6, pp. 20–22].

Cloud computing security was not listed deliberately among the advantages because the opinions differ on this matter. Some authors consider cloud solutions far safer than traditional protection mechanisms what in view of applied relevant procedures and technical solutions should be considered as more effective. On the other hand, the privacy and legislation cannot be underestimated.

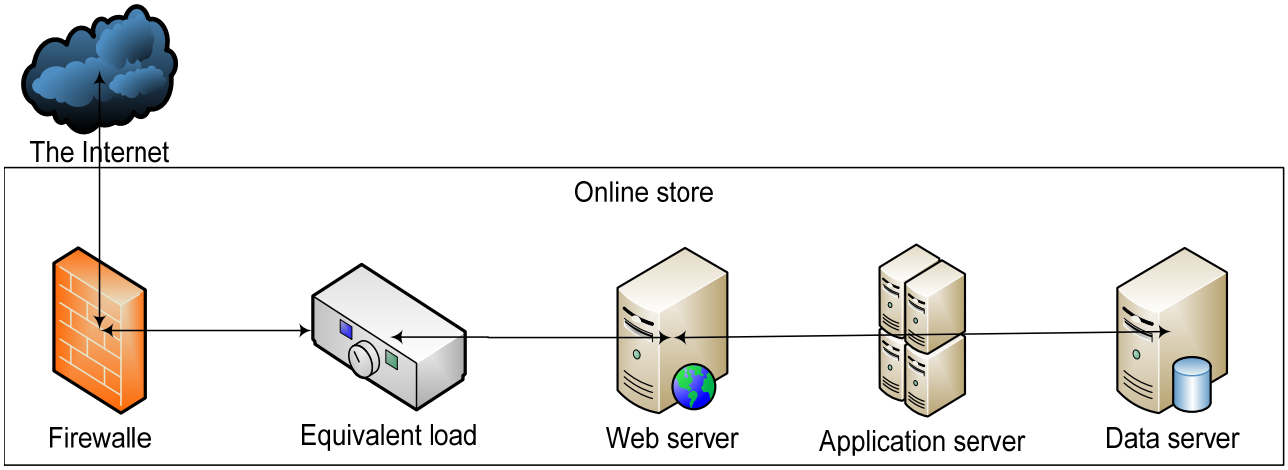


Figure 2. Elements of the IT infrastructure of the analyzed online store
(*source: own elaboration*)

Users storing and processing data in the cloud do not always know where their data are physically located and who and on what basis has access to them. Data breach is a big concern in cloud computing. Customers worry if provider cloud computing services informs them about any breach of security in their data centers. In addition, some companies offering cloud computing services has registered their offices outside the European Union and are not subjected to EU law, which may lead to lower standards of data security.

Disadvantages associated with uncertainties about the safety of the cloud computing services are multiplied, but limitations as dependence on software providers, the lack of readiness of employees to use the cloud, IT specialists' reluctance to potentially dangerous changes to their employment, internet links with insufficient bandwidth.

Considering the advantages and disadvantages, opportunities and threats related to the processing of data in the cloud should compute the type of cloud (public, private, shared, hybrid) and the range of services offered should be taken into account. Most of these benefits are available if the company chooses IaaS, PaaS, SaaS models. The adoption of these models is most profitable for the company providing more flexibility, lower costs and ease of use. In contrast, it is not so evident in the case of private cloud. In this case, the solution, in terms of costs and responsibilities, differs slightly from the classical data processing solutions. Because the data center is under the control of the company it dissolves the problem associated with legal provisions.

How to determine whether transition from the classical model to cloud computing model is cost-effective and which set of cloud services, determined by a combination of available service models, deployment models and types of clouds, is the best for the organization?

It seems that in order to answer this question, it is necessary to develop a method of balancing the costs and expected benefits of both classical and cloud computing solutions. Such a method should take into account not only the cost of construction and equipment of the server but also the speed of deployment of new functionalities, which have been shown on the example of a Rzeczpospolita newspaper multimedia service, the cost of qualified staff employing, operating costs and the costs of disposing of waste or unnecessary IT equipment.

## 3 Case Study

This case study demonstrates how company is planning within existing operations the creation of an online store selling sporting goods. The online store activities were to be maintained for three consecutive years. After this time, the decision to continue or discontinue operations might be made. The company has already created the necessary IT infrastructure including its own data center and qualified staff. To start a new project, a company must purchase additional hardware. All new hardware components are shown in Figure 2. To ensure continuity of service availability and to reduce outage duration each of the elements will be duplicated as presented in Figure 2. Project management assumes a stable IT infrastructure load without load surges.

Table 2. Cost of purchasing new IT infrastructure elements needed for launching an online store (*source: own elaboration*)

| Specification | Unit price | Number of items | Internal solution |
|---|---|---|---|
| Firewall | 4000 | 2 | 8,000 |
| Equivalent load | 14000 | 2 | 28,000 |
| Network server | 8500 | 2 | 17,000 |
| Application server | 8500 | 2 | 17,000 |
| Data server | 8500 | 2 | 17,000 |
| Total | - | - | 87,000 |

Free software will be used to minimize the building costs of an online store. Necessity to purchase a new hardware and the uncertainty whether the shop will continue to exist after the assumed time begs the question. The question may yet be raised in another case whether the cost of new IT equipment and launching of the project in the company's data center will be profitable. Is the lease of virtual stores an advantageous solution in the cloud computing formula?

Project management deciding to launch an online store in their own data center must bear the costs presented in Table 2.

The cost of purchasing the necessary elements of the IT infrastructure for launching an online store in their own data center is at the level of about 87,000 PLN. Assuming a three-year period of the project, the cost is 2416,67 PLN per month. The total amount must be paid in advance. The calculation applies only to the purchase of necessary new infrastructure elements. Costs not taken into account include:

- power supply of purchased equipment,
- cooling of purchased equipment,
- server rack space,
- internet connection (for example, an additional link 10 Mb–3000PLN per month),
- staff remuneration (administrators and technicians),
- staff training.

These cost categories are not included in further analysis because they are already paid by the company, which maintains its own data centers. The increase in operating costs due to the purchase of new IT equipment makes only small part of total costs and would be considered insignificant. Therefore, we are not going to analyze those costs any more.

Summing up the cost of launching, an online store in the enterprise data center, the adopted assumptions that month about 2,400 PLN at a three-year term adds up to about 87,000 PLN. However, there is a possibility that after this planned period the project will be liquidated as unprofitable. If this happens, the company remains with unused network equipment that should be maintained or to bear the costs of disposal.

An alternative solution to eliminate the problem of unnecessary IT equipment is to launch an online store in the cloud computing environment. Starting a project within cloud computing formula offers cost savings because of "pay-as-you-go" services with no contracts, and often no sign-up fees and just we pay for what we use, e.g. RAM, CPU, hard drives.

A company to run an online store in cloud computing instead of buying physical hardware purchases its virtual counterparts. Table 3 presents a summary of virtual instances offered by Amazon, Microsoft and Polish company. Unlike Amazon and Microsoft, Polish company does not offer predefined instance but allows configuration of a virtual server according to client's needs. In case of Amazon Medium Instance, it corresponds to the physical server needed for the planned creation of an online store. And Microsoft Large Instance meets the requirements of the project. To ensure the comparability of virtual instances for Polish company, identical parameters for virtual servers as for the selected instance Amazon shall be adopted. Instances replace virtual IT infrastructure elements such as a network server, application server and data server. It is necessary to take out six virtual instances to replace six physical servers of assumed IT structure. To build a comprehensive IT infrastructure, a service must be purchased to replace the firewall and server load equivalent. Table 4 gives the monthly rental cost of such services in comparable companies assuming that the services are still available for all rented instances.

Table 3. Summary of virtual instances offered by Amazon, Microsoft and Polish company
(*source: [2, p. 150, 7, p. 84], Polish company offer*)

| Specification | RAM (GB) | Processors | Data warehouse (GB) | Platform (bits) |
|---|---|---|---|---|
| • Amazon | | | | |
| - small | 1.7 | 1.2 GHz | 160 | 32 |
| - medium | 7.5 | 4×1.2 GHz | 850 | 64 |
| - large | 15 | 8×1.2 GHz | 1690 | 64 |
| • Microsoft | | | | |
| - extra small | 0.768 | 1 GHz | 20 | 32 |
| - small | 1.75 | 1.6 GHz | 225 | 32 |
| - medium | 3.5 | 2×1.6 GHz | 490 | 64 |
| - large | 7 | 4×1.6 GHz | 1000 | 64 |
| - extra large | 14 | 8×1.6 GHz | 2040 | 64 |
| • Polish firm | | | | |
| - client configuration | n×1 | n×1 GHz | n×1 | 32/64 |

Table 4. Summary of cost of services
(*source: [7, s. 84–86], Polish company offer*)

| Specification | Virtual VPN | Virtual load balancers |
|---|---|---|
| Amazon | 622,00 PLN | 72,00 PLN |
| Microsoft | 600,00 PLN | 94,00 PLN |
| Polish firm | 300,00 PLN | 15,00 PLN |

Table 5. Simulation of the transfer and storage of data costs
(source: [7, pp. 84-86], Polish company offer)

| Specification | Data transfer | Data storage |
|---|---|---|
| Amazon | 32,50 PLN | 855,00 PLN |
| Microsoft | 35,00 PLN | 850,00 PLN |
| Polish firm | 90,00 PLN | 900,00 PLN |

Estimated costs of building an online store in the cloud computing formula must include costs resulting from the provision of IT infrastructure and additional costs resulting from launching the project outside of their own data center. They include data storage and data transfer. Table 5 shows the costs of these services in the analyzed companies. The objectives of the simulated costs are:

- data transfer not exceeding 1TB per month,
- stored data not exceeding 2TB.

Table 6 summarizes all categories of costs for launching an online store, both in their own data center and hiring the necessary IT infrastructure in the cloud computing formula.

Table 6. Total costs
(*source: own elaboration*)

| Specification | Cost of own launching | Cloud computing cost Amazon | Cloud computing cost Microsoft | Cloud computing cost Polish firm |
|---|---|---|---|---|
| Virtual VPN/firewall | 222, 22 PLN | 622, 00 PLN | 600, 00 PLN | 300, 00 PLN |
| Equivalent load | 777, 78 PLN | 72, 00 PLN | 94, 00 PLN | 15, 00 PLN |
| Virtual network server | 472, 22 PLN | 2 172, 00 PLN | 6 498, 87 PLN | 8 913, 00 PLN |
| Virtual application server | 472, 22 PLN | | | |
| Virtual data server | 472, 22 PLN | | | |
| Data transfer | 0, 00 PLN | 490, 00 PLN | 35, 00 PLN | 290, 00 PLN |
| Storage of data | 0, 00 PLN | 855, 00 PLN | 850, 00 PLN | 900, 00 PLN |
| Total monthly costs | 2 416, 67 PLN | 4 211, 00 PLN | 8 077, 87 PLN | 10 418, 00 PLN |
| Total cost after 3 years | 87 000, 00 PLN | 151 596, 00 PLN | 290 803, 31 PLN | 375 048, 00 PLN |

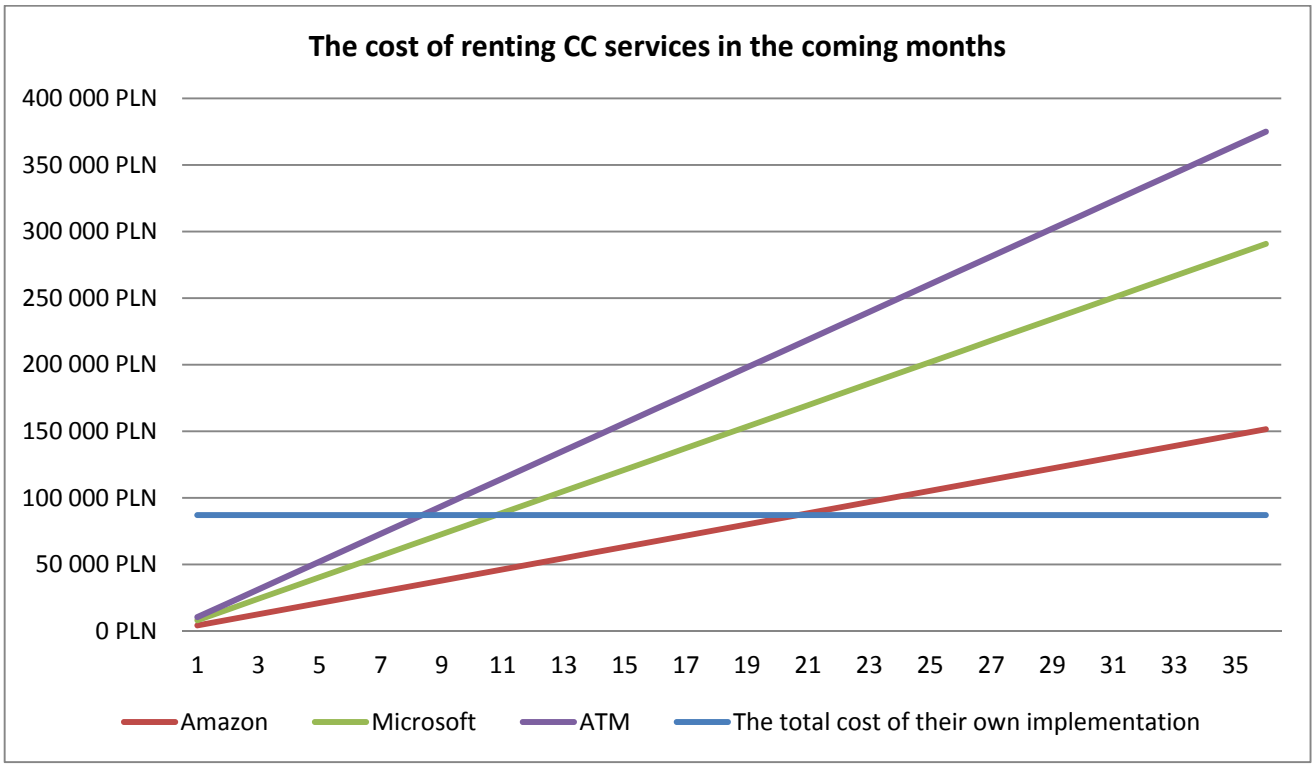


Figure 3. The costs of renting cloud computing services in the coming months
(*source: own elaboration*)

Figure 3 shows the change in the data in Table 6 during 36 months operating of online store. Graph analysis reveals that the assumed period and IT infrastructure requirements for launching an online store in cloud computing formula must be considered as uneconomic. The total cost of provisioning additional hardware for the project to be launched in their own data center is generally estimated at 87,000 PLN. This amount is exceeded by all the analyzed cloud providers' bids. In the case of Amazon, it occurs after 21 months, Microsoft after 11 months and Polish company after 9 months.

Chart analysis draws attention to the time of service operation, which turns out to be very important and must be included in a proposed method for the selection of cloud computing services for the organization.

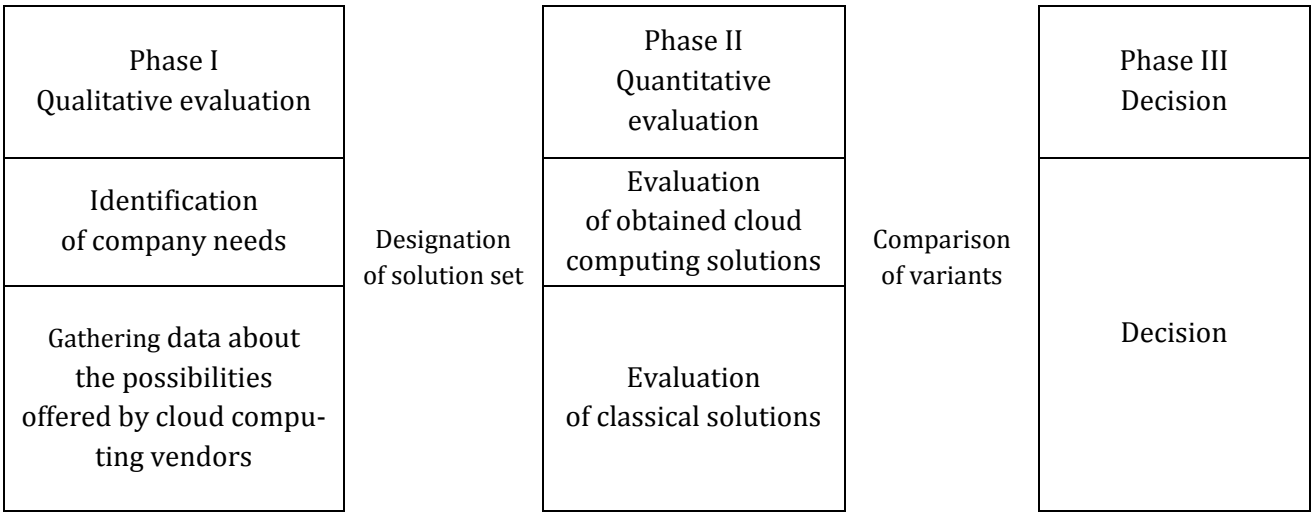


Figure 4. Model making decisions on the use of cloud computing in the enterprise (*source: own study*)

The discussed example also brings some assumptions and simplifications that had to make it more understandable. All these elements are integral part of a general methodology of the proceedings.

There are many combinations of these factors as well as factors affecting the viability of the use of a specific enterprise in the cloud computing including the following:

- status of the business (start or continuation),
- having or not their own data center,
- having or not the skilled workers of IT department,
- the complexity of the IT infrastructure,
- operation time of the projects,
- presence or absence of high loads surges of IT infrastructure,
- applied software.

The multiplicity and diversity of decision-making areas according to the author determine the need to develop a methodology clearly defining the criteria that should be taken into account, and present a method to deal with the process of collecting the necessary data and making decisions. Previous analysis of literature sources did not reveal the existence of such a method.

## 4 Research methods

As a result of presented cloud computing services in the previous chapters, the author proposes a three-tier cloud computing model of decision-making on the use of outsourcing IT services in the enterprise (see Figure 4).

The proposed first stage of the procedure involves two elements. First, the company needs to determine their requirements for IT infrastructure. Such a document should include information about the assumed minimum and maximum demands: main memory, disk storage, computer performance,

Internet bandwidth, load estimation infrastructure at critical moments and the duration of such a load along with its frequency, etc. Identification of the necessary data by many businesses, especially in the sector of small and medium-sized companies, can make an insurmountable barrier. Therefore, the proposed approach is to develop a model document that will contain the necessary parameters and guidelines to support the estimation process.

The second element of the first stage should include the collection of data on the possibilities offered by the cloud computing. Here, it is also advised to develop a set of basic information about the cloud computing services, updating them together with the market development, and sharing them with companies considering the implementation of cloud computing..

Finally, the comparison of the two sets of information should lead to a selection of those solutions offered by the cloud computing, which meet the company requirements.

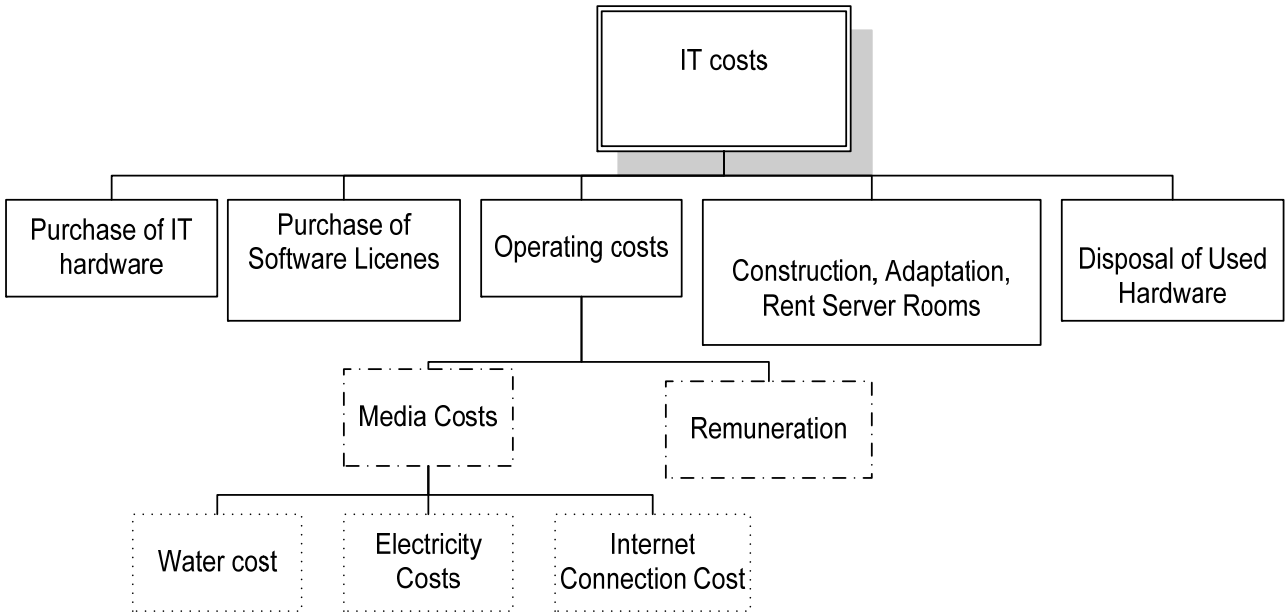


Figure 5. Diagram of the costs associated with IT infrastructure
(*source: own elaboration*)

In the second stage, the company having a set of possible solutions meeting their requirements and taking into account various vendors should proceed to the valuation of the cloud computing solutions. Then, the cost of launching the necessary infrastructure within the organization should be specified. Estimating the cost of deploying IT infrastructure in-house, a company should take into account several aspects: the cost of purchasing IT equipment, the cost of construction or adaptation server rooms, operating costs, infrastructure maintenance, waste disposal costs of IT equipment and other devices of the server rooms such as air conditioners or the time needed for IT infrastructure to support the project. Figure 5 presents a diagram of IT department costs.

After obtaining the necessary quantitative data, the company managing board should come to a decision about the application of one of the available solutions. It should be emphasized that decision making guided by the criterion of the lowest price is not always the right one. One can imagine a situation in which the difference in costs between classical data processing and cloud computing services might be so insignificant that taking into account the development and probably the cost reduction in cloud computing services, the company decides to outsource IT infrastructure.

The application of presented approach should be determined on the operating expenses of IT infrastructure used in the enterprise. Unfortunately, the lack of methods for estimating such costs makes it very difficult. Institute for Market Economics in its report in 2011 estimated that 80% [8, p. 29] of IT budgets are spent on maintaining current IT infrastructure; however, the data may vary in companies and should be verified.

This brings up the research questions:

1. What is the level of operating costs incurred for the maintenance of the IT infrastructure of the organization?

2. What is the break-even point for the maintenance of own IT infrastructure?

3. What is the trend in costs of cloud computing services and when the cost is low enough that it would be uneconomic to maintain their own IT infrastructure?

Taking an attempt to answer these questions, the author proposes a two-stage study. The first step assumes the development of a questionnaire addressed to all employees of the company. The purpose of the survey is to collect information about IT equipment (corporate and private) used by employees and the time allocated to the usage of each device. The second stage of the study should determine the level of energy and water (in the case of air conditioners) consumption per each unit of IT infrastructure. For that purpose, necessary will be the use of special measuring equipment's connected to every device separately. Collected survey data, media consumption measurement data and employee remunerations allow the author obtaining a nec-

essary knowledge about the level of operating costs of maintaining the IT infrastructure of a company.

Gathering data on the media consumption from the suitable number of organizations helps to determine the average values for different types of IT infrastructure devices what significantly will facilitate the application of the method in organizations, which will not be in a position to finance the second stage of the investigation.

In conclusion, the proposed method consists of three steps. The input to the first stage is information about the internal needs of the company and details about the capabilities of cloud computing services providers. In this way, it becomes possible to reject those solutions that do not meet the organization data processing requirements. Solutions that meet the company requirements together with the knowledge of the costs of the various solutions are making a set of input data for the second stage of the proceedings. Thus, a ranking of possible solutions structured by cost comes into being. The third stage is a decision-making process that attends to imply the best solution in the company.

## 5 Summary

Referring to the question posed in the introduction, it should be noted that the cloud computing service in its current form is not the most advantageous solution for any organization. Cloud computing reliability is not guaranteed in matters relating to security, which is of great importance for banking and insurance companies. Another major limitation is the data transfer rate through the Internet that prevents the use of computing potential power delivered by large data centers. On the other hand, cloud computing solutions perfectly suit the cases where data should be made publicly available, e.g. multimedia services. Then, we can enjoy the full benefits of what brings cloud computing.

Considering the limitations and imperfections of current cloud systems, it appears advisable to develop a quantitative method to determine whether the use of cloud computing or the transition from the classical model of data processing into one of the cloud computing models is profitable. It should be clear that cloud computing service is not homogeneous and must be considered in the context of a specific deployment model, service model and type of cloud. It is recommended that for such definite matrix, areas defined by three dimensions should be developed for each a set of advantages and disadvantages, opportunities and threats to the organization. A SWOT analysis can be carried out for this purpose. Such an analysis should answer the expectations of the company, creating a first step in qualitative method, contributing to the selection of cloud computing services corresponding to the organizational model. A second step should take place after identification of an appropriate set of cloud computing services, which leads to the question of whether the transition to a new model of data processing will bring savings in relation to the status quo. To achieve this objective, the areas that generate data processing costs should be identified including: purchase cost of equipment, license fees, maintenance of infrastructure, implementation of new functionality and many others. Subsequently, it is necessary to choose appropriate measures for the identified areas and develop a model to estimate costs.

The author, considering presented material, considers a thesis statement that for the purpose of proper selection of cloud computing service it is necessary to apply qualitative analysis, which allows comparing the costs of selected type with other data models. The particulars of the outlined method applied for selection of cloud computing services are the subject for further research.

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# V.A. GORBATOV THEORY OF CHARACTERIZATION – PRINCIPLES AND EXAMPLES

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***Abstract:*** Characterization theory was developed in the 1970s by a member of the Russian Academy of Sciences, a prominent cybernetics V.A. Gorbatov, and became the nucleus of an international school. Many of today's academy graduates make a new generation of scholars, more than 150 doctors and assistant professors, developing a new descriptive theory of cybernetic complex systems, based on the canon of the so-called characterization principle, binding the sets of $\Psi_a$ functioning models and $\Psi_b$ structure models using the paradigm of monotone mappings of the considered system. This article presents an overview of the following problems: (1) the issues of functional–structural connection systems from the point of view of their design correctness; (2) the basic postulates of the characterization principle; (3) the nature of interaction between system objects; (4 and 5) mechanisms and functions for initiation of the operation; (6) the mechanisms of control and reaction functions; (7 and 8) the analytical form of initiation function and a network initialization function and (9) the axiom of extensionality (J), feasibility (R) and compatibility (Z).

***Keywords:*** functional model, structure model, atomic predicate, characterization principle, operations and functions of initiation, control and response functions, axioms of clarity, feasibility and compatibility.

## 1 Introduction

The essence of the characterization principle is expressed in mutual interpretation of the $\Psi_a$ functioning model of a certain object (resource) with the $\Psi_b$ structure model.

Reciprocal interpretation of $\Psi_a$, $\Psi_b$ models is achieved by the selection of universal rules of "proper" functioning model $\Psi_a$ and expressed in the $\Psi_b$ model structure. Rules of proper functioning are determined by the obligatory, forbidden and neutral figures of $\Psi_a$ functioning model. Due to the graphic form of their structure, these figures are often called graph figures.

The idea of the proper functioning of a specific object [3, 4] can be expressed through mutual interpretation of $\Psi_a$ $\Psi_b$ models in the following way:

- object functions adequately to its structure described by $\Psi_b$ model structure and
- object structure is adequate to its desired way of functioning described by $\Psi_a$ functioning model.

A basic model of the characterization theory can be described as:

$$< \Psi_a, \Psi_b, P_o(\Psi_a, \Psi_b) > \quad (1)$$

where $P_o$ $(\Psi_a,\Psi_b)$ is an atomic predicate characterizing the interpretation possibility of $\Psi_a$ functioning model in the categories of $\Psi_b$ structure model.

Satisfactory interpretation is obtained if $\Psi_a$ functioning model (e.g. solution model) is stored in the form of proper functioning axioms expressed in the form of obligatory, forbidden and neutral graph figures. Such an approach allows creating flawless (and also optimal) solution design tasks while avoiding a time-consuming procedure of testing directly the structure of (prototype) solution.

The difficulties in verifying the proper functioning of the object by applying tests lies in the fact that, in real terms, we are not able to see all the possible variants of the structure. The unlimited storage of the object in question or the memory of its environment (the environment in which it operates) is practically an obstacle.

Known methods of system design are the "trade" answers how to create structural network architecture solutions, how to build machinery and equipment and how to design processors and computer programs. Universal design method for all structures does not exist, although from system positions, "trade" struc-

tures become more and more similar to each other (homeomorphic).

The computer virtual space is already able to hold "almost everything" what is coming into existence from the imagination of engineers. In this context, it is reasonable to formulate universal reference examples or functional–structural paradigms, understood as special design theories. Characterization principle determines the general direction of theoretical works but $\Psi_a$, $\Psi_b$ models and atomic predicates are constructed for a specific class of tasks and their resources.

## 2 Functioning and structure

A relationship between functioning and resource structure is considered as a necessary for the whole of analytical synthetic methods for decomposing and solving any design tasks.

The first theoretical solutions to the structural–functional relationships were developed by V.A. Gorbatov in his works on a partially ordered sets, particularly on the synthesis of logical structures and their imaginary drawing of Hasse diagrams [3,4]. Continuation of these studies led to the formulation and development of the characterization principle for the task of designing complex technical and organizational systems [5-7, 11, 16].

The nature of characterization principle is determined by the $\Psi_a$ functioning model connected with the $\Psi_b$ structure model using $P_o(\Psi_a, \Psi_b)$ predicate, characterizing the interpretation possibility of functioning model in the categories of $\Psi_b$ structure model. In case of designing the structure of interested us system, the characteristic principle comes down to interpretation of the $\Psi_a$ model (the assumed logical, temporary and priority connections) in the $\Psi_b$ model categories of the resource structure of this system. Such an interpretation is achieved through axiomatic proper functioning and graph figures of $\Psi_a$ model.

The necessary condition for the correctness of project is the presence and absence of homeomorphic graph figures adequately to obligatory and forbidden graph figures. The fundamental problem in designing constitutes synthesis and seeking such figures. In return, we are given the opportunity to avoid errors in the system design project without the need to time-consuming and costly testing of structures with the complexity of P expressed in the form:

$$P = \prod \varkappa_i! \tag{2}$$

where $\varkappa_i$ is the number of elements of the storage device and the twig-Hasse (e.g. for seven 5-elements twigs of Hasse $P = 38.8 \times 10^{12}$).

In case of system resource interpretation, the theoretical interpretation of specific changes in the value of its input and output characteristics is determined by the structure and functioning of the resource. System resources will function properly if between their functioning rules and structure a mutually synonymous interpretation is determined including the following assumptions:

- system functions adequately to its structure, and
- resource structure is adequate to its desired way of functioning.

Examining functional–structural connections constitutes the basic paradigm of the theory and practice of the systems design. Software engineers develop appropriate structures to achieve the desired functioning of existing or hypothetical objects. Design theories compose to some extent "trade" answer how to create architectural solutions, how to build machinery and equipment, how to design processors and computer programs. There is no and it may not be a universal method for designing all structures, although from the point of system positions, the "trade" structures become more and more alike. Virtual computer space is already able to hold "almost all", which comes from the imagination of engineers.

In this context, it is reasonable to formulate universal examples or functional–structural paradigms, understood as specific design methodologies. Characterization principle sets the general direction for methodological work; $\Psi_a$, $\Psi_b$ models are constructed for a specific class of tasks.

Functional–structural paradigm is the characteristic for the project activity, which is looking for a structural response to a specific functional problem. This paradigm is in balance of structural–functional paradigm, where the functional interpretations (interpretations in the field of functional) are derived from the original structure. Structural–functional paradigm focuses equally on archeology, astronomy and art. In many practical situations, we cannot separate or indicate what is primary: functioning or structure?

The functioning of any object including, for example, any engineering system, is determined by the appropriateness which takes place between its structure (struc-

tural–static characteristics) and functioning (dynamic characteristics). It is possible to examine this suitability at different levels, in particular:

- at the level of abstract models and theories,
- at the level of program or physical simulation models,
- on the level of testing models and prototypes, and
- during the observation of working systems.

The practical importance of this type of analytical work includes giving directions for reducing workload and functionally optimized systems search. Such a feature is particularly important in the process of computer-aided design work applied to the methods of designing engineering systems. These are the methods that allow "browsing" through many simplified indirect solutions until the final versions in the form of complete projects have been generated.

Functional–structural paradigm raises the hypothesis of a constructive proving the unity of structural-functio-nal systems, understood as a theoretical ability to design functionally and structurally correct systems. For the purposes of this hypothesis:

- functional validity of the system should be understood as the ability to define a finite set of primary functional rules of the system for which will be created such a practical possibility of their structural realization that the system will implement only primary functional rules,
- structural validity of the system should be understood as the ability to define a finite set of secondary rules of this model in the form of functional obligatory, forbidden and neutral graph figures that determine the functional validity of the system in terms of its set of primary functional rules.

Structural accuracy of the system is ensured if the model of functioning will meet these requirements:

- there will be no forbidden figures,
- obligatory figures occur,
- neutral figures will be used in the equivalent transformations to simplify the system structure without compromising its functionality.

## 3 Characterization principle in a specific project

Efforts to find the optimal variant of solution implies the need to generate and evaluate the set of all possible solutions that could potentially arise in a particular problem situation (in a given objective area) and the applied method. In the most practical design problems, the number of solution set elements grows in a combinatorial way, thus, any practical chances of finding "optimum solution variants" by scanning each of them fail. Therefore, it is necessary to use appropriate "simplifications" narrowing down the search space and accelerate the evaluation process. This becomes especially important in a situation where the complexity of objects grows to the order of magnitude of hundreds or thousands of items or if there is a need for a "smooth" change of the level of detail in analyzed situations. In such cases, we may be helpless against the multidimensionality of objective area.

Universal rules of proper functioning are expressed mostly by the so-called obligatory, forbidden and neutral figures operational model. These figures are also called graph figures because of their graphical form.

Obligatory figures of the functioning model are abstract constructions, which as homeomorphisms should occur in the functioning model under the "threat" of their incorrectness. Forbidden figures of the functioning model should be easily identifiable objects. Isolation or dispersion (in the functioning model) assures the functional correctness of the object.

Neutral figures are used to make simplification transformations of the functioning model, which do not result in forbidden and obligatory figures. Neutral figures play the role of "system builder" in this proceeding that can be removed or added without affecting the validity operation of the entire object. Elimination of neutral figures to ensure functional correctness leads to an effective simplification of the object model and, consequently, to reduction of the combinatorial computations.

In case of any object (resource), the theoretical realization of certain changes in the value of its input and output channels (features) is determined by its structure (hierarchical memory) and its functioning. An object will operate correctly if there is a mutually synonymous interpretation expressed between functioning rules and structure, which might be determined on the following assumptions:

- object (resource) functions adequately to its structure and
- object structure (resource) is adequate to its desired way of functioning.

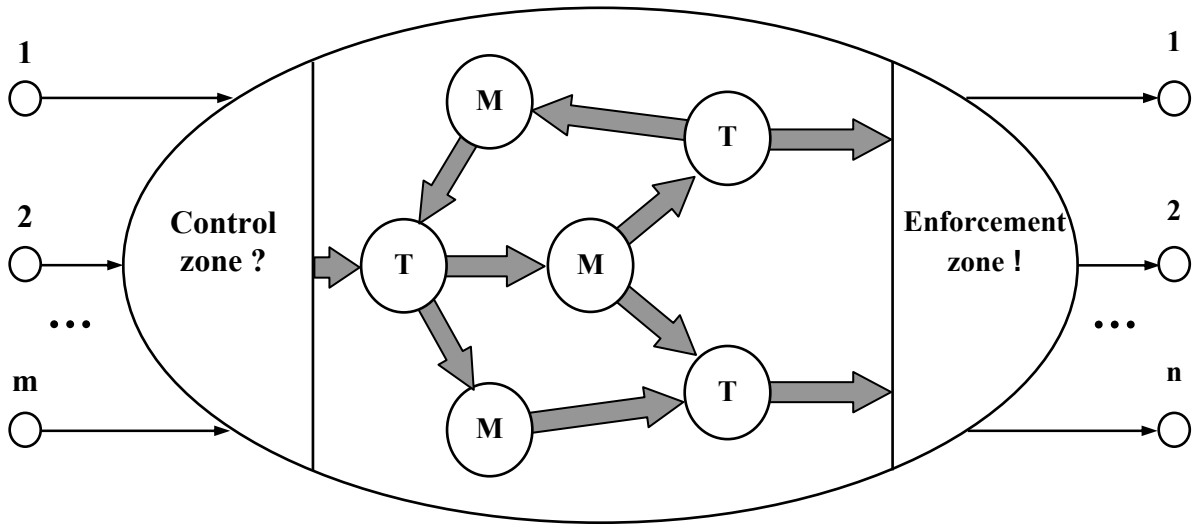


Figure 1. Object as a finite state machine

The study of functional–structural connections constitutes a basic paradigm of interests in management sciences (formerly the organization and management sciences) born of engineering activities. It is essentially a domain of theorist and designer engineers developing appropriate structures to achieve the intended operation of existing or hypothetical objects.

From the methodological point of view, the application of characterization principle for solving design problems makes a very promising approach that can be successfully used, provided that for a given problem area will be created an adequate characterization theory in the form of a basic model of the theory (1).

## 4 Objects, channels and channel operations

The theory of given physical reality sets out the principles of this reality existence through the system of semiotic signs being a synthesis (model) of the operation specifications.

The term "object" is used for modeling a relatively constant structure of interacting facts. Object in the sense of external behavior similarity can also be interpreted as a finite state machine (Fig. 1). The way of combining objects into the configurations of objects (Fig. 2) and the internal mechanism of interaction processes of the object make the main differences. On the basis of the inspection results, operation carried out in the control zone at input channels in the object, appropriate operations of forcing its output channels are taking place in the excitation zone. It is possible to distinguish in the object m input channels and n output channels and certain conventional procedural interaction zones. Each channel is related to a finite alphabet of the channel states. The zones of procedural impacts:

- control zone states of the input channels (designation: ?)
- enforcement zone states on the output channels (designation: !)
- transformation zones of the interaction results (processing zone) connecting the two aforementioned zones (designation: T) and
- object memory zones (designation: M).

Object configuration creates a parent object. In Figure 2, such an object is $O_5$ whose input and output channels (channels $K_{1,0}$ and $K_{1,5}$) connect internal objects (objects $O_2$, $O_4$) with the environment. Any output object channels can be an input channel of one or more configuration objects or its output channel. Object channels are capable of autonomous memorizing their own state. Object interpretation of reality can be carried out in such a way that the entire internal memory of any object will be expressed in the form of its output channels and its output channels of internal objects.

A subset of the output channels $KW_Y$ of object $\mathbf{O_i}$ will be called characteristic channels of this object. Each channel can be a characteristic channel of only one object and at the same time can be commutated with input channels of many other objects (output channel object can be used at the same time as its input channel). This situation is illustrated in Fig. 2.

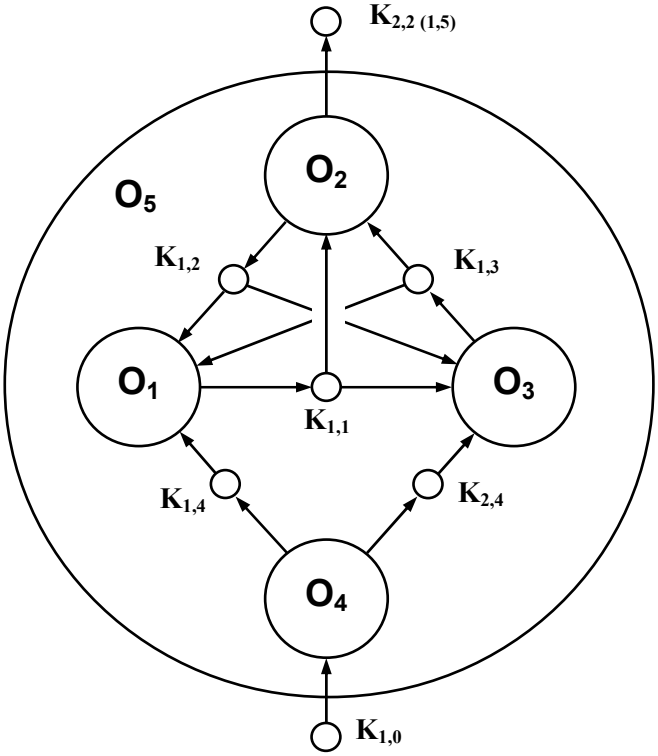


Figure 2. Object configuration

Each characteristic channel of object $\mathbf{O_i}$ is associated with repertoire of states S determining the all possible states of the channel. The characteristic channel of object $\mathbf{O_i}$ may be at any point of time only in the $S_i$ state belonging to the repertoire of the channel states.

The status of the characteristic channel object $\mathbf{O_i}$ is defined by the enforcement procedure carrying out the impact of this object on its environment.

The internal processing of the object is directed (described) by the operation procedure of the object, which in general it may assume a stochastic (random) character. The reading-out of input channels states and excitation in accordance with its model of functioning and the states correctness of output channels should be ensured by operating procedure for the object at any opportune moment. The functioning procedure for operation of object should accomplish the constitutive goal of the object.

## 5 The beginning of operation

The implementation of discreet process is determined by the starting (initiation) of appropriate enforcement operations and control of events of this process. The purpose of initiation is only the "recovery" of procedure, which executes on the channel object the enforcement of event (change of state) or the control of its occurrence (changes observation status).

Initiation of operations on channels is carried out by the initialization function network (Section 7). This approach is achieved by:

- separation excitation and control processes from internal computing processes of the function initialization system,
- the possibility of constructing multi-level (hierarchical) control systems,
- the possibility of using the modeling apparatus of concurrent processing for the design of distributed control systems for objects of distinguished sets of input and output channels on which there are implemented allowable sequences of events.

Because of the separation of procedures implementing excitation and control operations from the computational processes of initiation function system, it is possible to use the multiprocessor solutions (distributed or implemented in a single computer, e.g. in a parallel architecture). In this case, each enforcement or control operation may correspond to one physical processor controlling all parameters of the operation. This type of solution also allows easily changing the time parameters and priorities of events during the initiated operation.

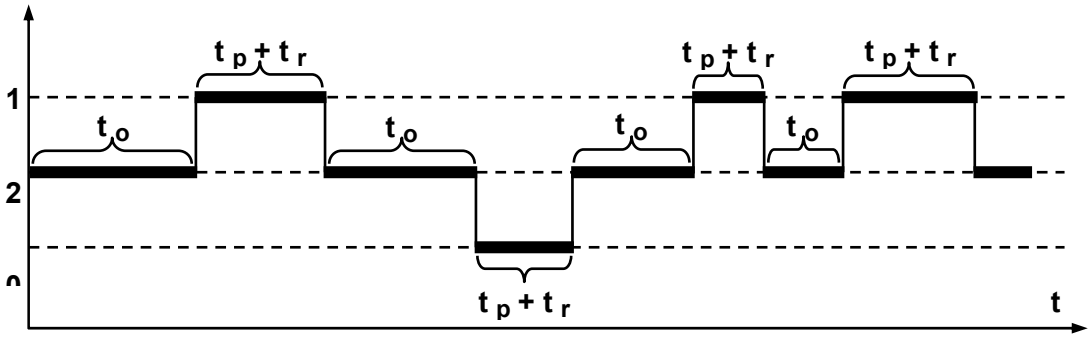


Figure 3. Timing diagram of changes in the function of initiation

Due to the discrete events and operations, it is also possible to use a special modeling apparatus of concurrent processes, for example, as Petri net, transforming network (T-network) or event algebra [10, 11, 13]. This apparatus is particularly suitable for the design of asynchronous control systems for discrete objects.

## 6 Initiation functions of the operation on object channels

Initiation function $I_i \in I$ is interpreted as the initiation of enforcement operation (more precisely: the initiation of enforcement procedure for implementing the enforcement operation) or as an initiation control operation (initiation control procedure implementing the operation of control). These operations are carried out outside of the network **N** of initiation function and for us the only important thing is the result of their execution, described by control functions $C_u \in C$ and response functions $R_x \in R$. The initiation function is thus a representative of the control or enforcement operations that through appropriate control and enforcement procedures are implemented by the considered object on the channels connecting it with other objects.

The control function $C_u$ shapes the result (effects of the operation at channels) carried out by the enforcement procedures (designation: $Q^!$) and control procedures (designation: $P^?$) executing, respectively, enforcement and control operations.

The reaction function $R_x$ is determined as a response of the initiation function environment to the enforcement or control operations.

Initiation functions I, control functions C and the reaction functions R assume the values from the set {0, 1, 2} in accordance with the following diagram:

$$0 \leftrightarrow 2 \leftrightarrow 1 \tag{3}$$

which shows that the change in a value of 0 to 1 (and vice versa) is possible only through a value 2. Value 2 plays the role of a neutral background, which is used for various purposes resulting from the model or technical reasons.

In case of initiation function $I_i$, interpretation of the function value is as follows:

0 – operation corresponding to the function $I_i$ is not initiated at a particular moment;

1 – operation is initiated at the point in time when the function $I_i$ assumes the (4) value of 1;

2 – operation is not initiated and it is not possible also explicitly to determine whether this operation will be or will not be initiated in subsequent moments of time.

Function $I_i$ returns a value 2 at the time when all assigned reaction functions to it will return to a value of 2.

Fig. 3 shows a timing diagram of allowable changes in the function of initiation. These changes occur as a result of the completion of the various phases of internal computation processes (calculation of the control and response functions assigned to the initiation functions immediately preceding the initiation of the function on the initialization function network, Section 9), and as a result of the starting procedure assigned to a specific initiation function. The duration of value 1 or 0 of single initiation is a total propagation delay ($t_p$) of these values, which refer to the control function and a period of time of value 0 or 1 ($t_r$ response time) of the appropriate reaction function, assigned to a particular initiation function. The duration of the value 2 of the initiation function is a computation time ($t_o$) of value 0 or 1 and the arguments (reaction function).

## 7 Control and response functions

The result of the operation of enforcement procedure $Q_u^!$ or control procedure $P_u^?$ is the control function model of $C_u$. The result marked as $[Q_u^!]$ of enforcement procedure $Q_u^!$ indicates a positive ($C_u = 1$) or a negative result ($C_u = 0$) of the enforcement operation (the events on channel object occurred or not occurred in accordance with reference sequence). The result marked as $[P_u^?]$ of control procedure $P_u^?$ indicates events compatibility on the channels with their expected sequence ($C_u = 1$) or the lack of such compatibility ($C_u = 0$).

Interpretation of the control function of $C_u$ for enforces procedures is as follows:

0 – if enforced sequence of events is different than assumed in the pattern specified in the function of control parameters $C_u$
1 – if enforced sequence of events has been implemented in accordance with the pattern (5)
2 – the required time for carrying out the sequence of events determined in the pattern has not yet passed or the realization of events has not started yet.

Interpretation of the value of the control function of $C_u$ for the control procedure is as follows:

0 – controlled sequence of events is not consistent with the pattern stored in the function of control parameters $C_u$
1 – controlled sequence of events has been implemented in accordance with the pattern; (6)
2 – control of events has not yet been completed or not started at all

Figure 4 shows a timing diagram of permissible changes of $C_u$ control functions in case of the enforcement procedure $Q_u^!$, and Figure 5 presents the case of control procedure of $P_u^?$. Changes as a result of the completion of various phases of the enforcement and control operation are taking place, respectively (after suspension of $t_z$ on a particular channel operation and after the time of enforcement $t_w$ or after the control of $t_k$).

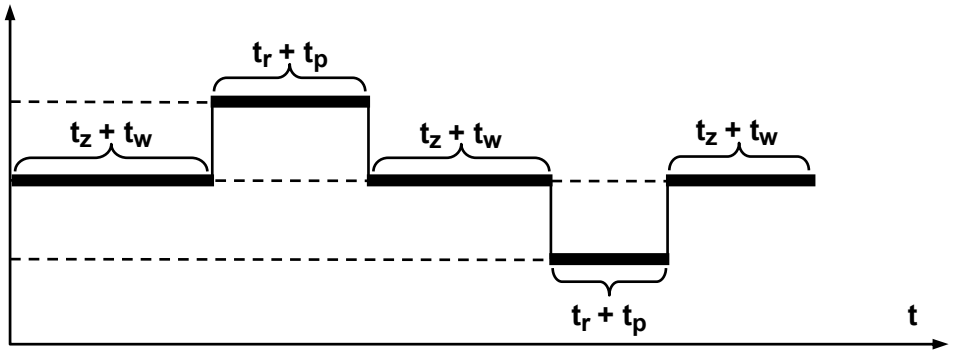


Figure 4. Timing diagram of changes in $C_u$ control function for the enforcement procedure $Q_u^!$

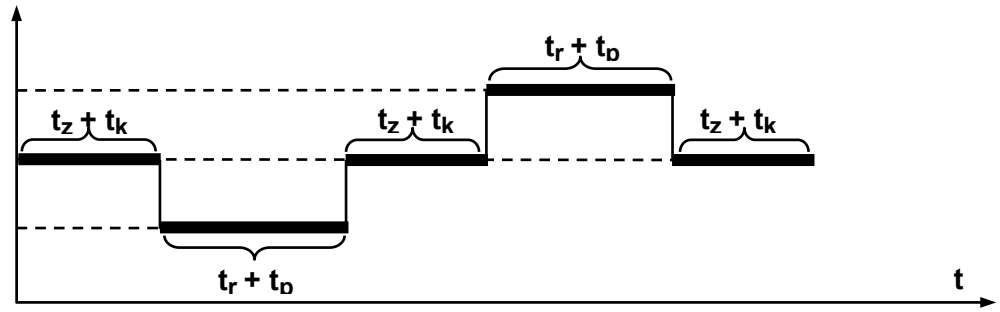


Figure 5. Timing diagram of changes in $C_u$ control function for the control procedure $P_u^?$

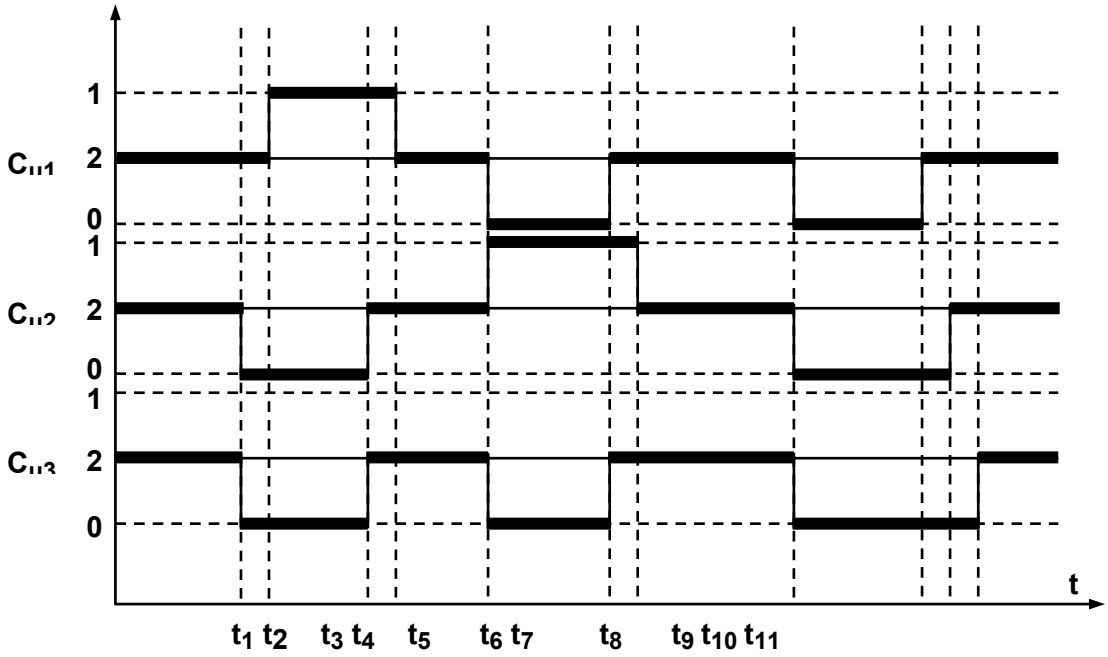


Figure 6. Timing diagrams of the value changes in the sequence $<C_{u1}, C_{u2}, C_{u3}>$ of elementary control functions

Values 0, 1 of control function are returning to a value 2 when the response function corresponding to a specific control function returns to a value 2 (after reaction time $t_r$ and propagation delay $t_p$ of the value of reaction function). In case of the enforcement procedure, a value 0 may indicate the emergence of higher priority sequences of enforcement events on a specific channel than the priority sequence of events currently being implemented, which results in interruption of the enforcement procedure. The appearance of the 0 function control, accompanying the enforcement procedure, can be also determined by the inability to start the operation of events sequence (e.g. due to the emergency disconnect from the channel control system).

Each control procedure $P_u^?$ has a sequence of at least two alternative patterns, which control the analysis of events on a channel. Each enforcement procedure $Q_u^!$ has only one pattern, which determines the implementation of the events on a channel.

In the case of complex logical expressions (trivalent logic), a value of the control function $C_u$ may be modified by logical operator E which depends on its own state of $[E] \in \{0, 1, 2\}$ and executes one of the three transformations $[E]C_u$:

- inversion ([E] = 0),
- identity ([E] = 1),
- or background ([E] = 2).

The following join dependencies should be fulfilled:

$$\begin{array}{lll} [0]\,0 = 1 & [1]\,0 = 0 & [2]\,0 = 2 \\ [0]\,1 = 0 & [1]\,1 = 1 & [2]\,1 = 2 \\ [0]\,2 = 2 & [1]\,2 = 2 & [2]\,2 = 2 \end{array} \quad (7)$$

Control function $C_u$ for control procedure $P_u^?$ is denoted as elementary sequences of control function ($C_{ui}$, ... ).

$$(C_{u1}, C_{u2}, ..., C_{un}) \quad (8)$$

Control function $C_u$ for control procedure $Q_u^!$ is denoted as a single element of the sequence:

$$(C_{u1}) \quad (9)$$

The following restrictions are applied on the control function of $C_u$, defined as a sequence:

- any element $C_{ui}$ can adopt only the values from the set {0, 1, 2}; it also refers to the sequence of a single-element function ($C_{u1}$); the change of the items value $C_{ui}$ may occur only in accordance with the diagram,
- if at a particular moment one of the elements $C_{ui} = 1$, then the remaining elements of the sequence can achieve only the value 0,
- if at a particular moment one of the elements $C_{ui} = 0$, thus all other elements require a value 0, or one and only one element achieves a value 1, and the other elements a value 0,
- element $C_{ui}$ returns to a value 2 when the corresponding reaction function $R_x$ assumes a value 2.

The response function $R_x$ is denoted by expression:

$$R_x (I_i , [E]C_u) \quad (10)$$

and assumes values compatible with the following indication:

$$\begin{array}{ll} 0 & - \text{ if } I_i = 1 \text{ and } [E]C_u = 0 \text{ or if } I_i = 0 \\ 1 & - \text{ if } I_i = 1 \text{ and } [E]C_u = 1 \\ 2 & - \text{ if } I_i = 1 \text{ and } [E]C_u = 2 \text{ or if } I_i = 2 \end{array} \quad (11)$$

A value 2 for the function from the sets I, C, and R is treated as a background for changes in the value 0, 1 (2). It is considered arbitrarily that any of these functions may change its value only in accordance with the diagram limit changes $0 \leftrightarrow 2 \leftrightarrow 1$.

Logical operator in the considerations may be omitted (e.g. by setting E = 1 for all instances of E).

Each enforcement procedure $Q_u^!$ has only one pattern to follow and in accordance with it implements the events on the channel to which it is assigned.

The control procedure $P_u^?$ has a sequence of at least two alternative patterns, according to which the events control on a channel is analyzed.

The reaction function $R_x \in R$ is interpreted as a result of the work of control procedure $Q_u^!$ or enforcement procedure $P_u^?$. Reaction function $R_x$ is a model, which describes the results of initiation procedures. To determine the value of a single-response function, the following are necessary:

- initiation function value,
- control function value, and
- (in some applications) the value of logical operator associated with the control function.

Because the control function $C_u$ is defined as a sequence of elementary control functions ($C_{ui}$, ...), which correspond to the checked patterns of events, thus, the corresponding sequences of the reaction function can be assigned to this sequence

$$(R_{x1} , R_{x2} , ..., R_{xn}) \quad (12)$$

Elementary reaction functions $R_{x1}$ of the above sequence are used to build an analytical initiation function $I_i = \nabla(R , ...).]$

The sequence of reaction function changes its value according to the diagram $0 \leftrightarrow 2 \leftrightarrow 1$.

Any pair of elementary reaction function $R_{xi}$, $R_{xj}$ differs from others in their initiation functions $I_i$, $I_j$ in the sequence of reaction function.

A value of ($R_x$, ...) sequence is computed in the following way:

$$\begin{array}{ll} 0 & - \text{ if all } R_{xj} \in (R_x , ...) \text{ have a value other than 2, and at least one of them is equal to 0} \\ 1 & - \text{ if all } R_{xj} \in (R_x , ...) \text{ have a value equal to 1} \\ 2 & - \text{ if even one } R_{xj} \in (R_x , ...) \text{ is equal to 2} \end{array} \quad (13)$$

In computing the sequence of reaction function returns to the background value (and thus also return to its background value all the elementary functions of the reaction) at a time when the associated initialization function takes the value 1 or 0.

## 8 Analytic form of initiation function

The evaluation of initiation function value is based on the analytical form (formula) of this function

$$I_i = \nabla(R_x , ... )_s \quad (14)$$

where $\nabla$ is the symbol of alternative trivalent disjunction, which semantics are described by previously presented expressions, $R_x$ is the elementary reaction function, $(R_x , ... )_s$ represents the sequence of reaction functions.

A value of initiation function is determined as follows:

$$\begin{array}{ll} 0 & - \text{ if all sequences } (R_x, ...)_s \text{ have a value 0} \\ 1 & - \text{ if one and only one sequence } (R_x, ...)_s \text{ has a value 1, and other sequences have a value 0} \\ 2 & - \text{ if even one sequence } (R_x, ... )_s \text{ has a value 2} \end{array} \quad (15)$$

The hypothesis that there is at most only one such sequence $(R_x, ... )_s$ which can assume a value 1, makes an important limitation adopted in determining the value of initialization function $I_i = 1$. This assumption is fundamental to the whole nature of the computational process, which takes place in determining the function value of sets I, C and R.

The assumption of the existence of at most only one sequence $(R_k, ... )_s$, where 1 results from to the correct construction of valid computational processes in the initialization function networks. A value as an element of set {0, 1, 2} can be assigned only to sequence $(R_x, ...)_s$.

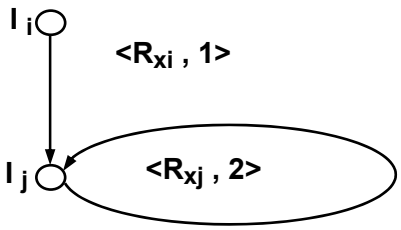


Figure 7. Cycle computations of initiation function

The value computations of the individual control functions, reaction function and initiation function must take place simultaneously (in parallel) for all functions. Hence, it is necessary to synchronize the processes of computation, which is particularly evident for the cycle computations where the initiation function $I_i$ occurs as an immediate or indirect operand for itself. Fig. 7 shows such a type of situation in the network of initialization function.

In accordance with the analytic form of initiation function

$$I_j = (R_{xi}) \nabla (R_{xj}) \tag{16}$$

where

$R_{xi} = R_{xi} (I_i, [E]C_{ui})$ and $R_{xj} = R_{xj} (I_j, [E]C_{uj})$.

In the considered example (Fig. 7), function $I_i$ is acting for itself as the immediate operand.

## 9 Network initialization functions

The network initialization function is a model setting formulas and computing order of initiation function. The network initialization function **N** is defined as a report:

$$<I, R, V, U, H_v, H_u, B^+, B^-, r, s> \tag{17}$$

where:

- I – set of initiation function,
- R – set of reaction function,
- V – set of nodes of the network graph,
- U – set of edges of the network graph,
- $H_v$ – is the function applying mapping of $V \leftrightarrow I$ ,
- $H_u$ – is the function applying mapping of $U \leftrightarrow <R_x, r, s>$,
- $B^+$ – is the function applying inductive coupling 0,
- $B^-$ – is the function applying coupling quench 0,
- r – index of edge output (relative to the graph node),
- s – index of edge input (relative to the graph node).

All sets are finite. Graph comprising a set V of nods together with a set U is a carrier network N. Graph network N contains two highlighted nodes $V_a$ and $V_b$ that indicate a path for any $V_j \neq V_a$ from $V_a$ to $V_j$ and for any $V_i \neq V_b$, there is a path from $V_i$ to $V_b$; $V_a$, $V_b$, $V_i$, $V_j \in V$. A node $V_a$ is called an initial node and $V_b$ node is called a final node of graph network. There is only one initial and only one final graph node in the network.

Function $H_v$ weights graph node of the network N using one function from the set I, and the function $H_u$ weights edge graph of network N by one function $R_x$ from a set R. The function $H_v$ applies monotone mapping of $V \leftrightarrow I$, and the function $H_u$ orders monotone mapping of $U \leftrightarrow <R_x, r, s>$.

Function $H_v$ weights each network node graph N using one initiation function in such a way that the different nodes correspond to different functions of initiation. Function $H_u$ weights every edge graph of network N using a set $<R_x, r, s>$ in such a way that the different input edges correspond to different sets. An edge directed from node $V_i$ to node $V_j$ (weighted by initiation functions $I_i$ and $I_j$) is weighted by compilation $<R_x, r, s>$, where the reaction function $R_x$ is determined analytically as $R_x (I_i, [E]C_u)$.

Index r is used for numbering and identification of outgoing edges of the nodes. A node numbering is carried out from 'left to right' counter-clockwise; if the index r is repeated in several combinations $<R_x, r, s>$ of outgoing edged of the same node, it means that they have a common elementary reaction feature (to the accuracy of the copy). Particular reaction function $R_x$ in formula is treated as an element of one and only one sequence $(R_x, \ldots)_s$ of index s, which is equal to the index of the compilation $<R_x, r, s>$. In case when it is necessary to repeat function $R_x$ in different sequences (combinations $<R_x, r, s>$), due to the synchronization of computation its copy are maid: $R_x'$, $R_x''$, ....

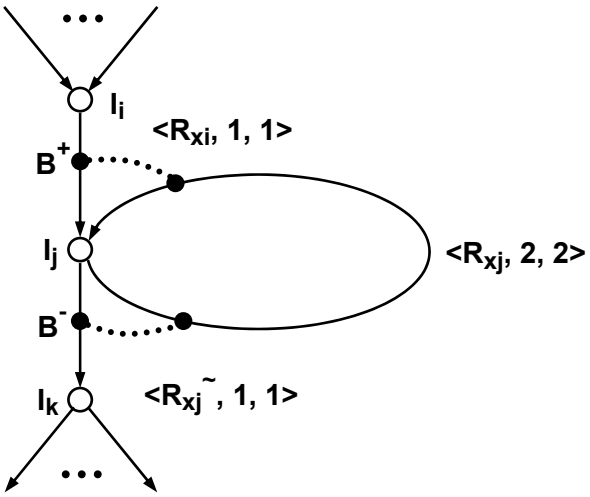


Figure 8. Example of a network fragment with sequences and couplings

$B^+$ is a function assigning inductive coupling of 0 and its main task is to induce a value of zero in one of the reaction functions covered by inductive coupling if the second function of the coupling reaction is equal to 1.

$B^-$ is a function assigning the dampening coupling 0 and its task is to suppress a value 0 (by changing to a value 2) for one of the reaction functions covered by dampening coupling if the second function of coupling reaction has a value 1.

An example of application functions $B^+$, $B^-$ is illustrated in Fig. 8. The corresponding calculation formulas have the form as follows:

$$\begin{aligned} I_j = &\ (R_i / R_j^+)_1 \nabla (R_j / R_i^+ / R_j^{\sim\sim})_2 \\ I_k = &\ (R_j^{\sim} / R_j^-)_1 \\ R_i = &\ R_i(I_i, [E]\, C_u) \\ R_j = &\ R_j(I_j, [E]\, C_u) \end{aligned} \qquad (18)$$

where:

$R_i / R_j^+$ denotes inductive coupling 0 for function $R_i$, if $R_j = 1 \Rightarrow (R_i = 0)$,

$R_j/R_i^+/R_j^{\sim}$ denotes inductive coupling 0 for function $R_i$, if $R_j = 1$ and dampening coupling 0 for function $R_j$, if $R_j^{\sim} = 1$ $(R_i = 1 \Rightarrow R_j = 0, R_j^{\sim} = 1 \Rightarrow R_j = 2)$

Edges weighed by combinations <$R_x$, r, s> and directed to the node $V_i$, which weighed by initialization function $I_i$, assign a subset of the reaction function R' onto which a function is determined. In turn, a subset of R' is distributed into disjoint subsets (sequences) $(R_x, ...)_s$ each of which corresponds to one index s and different indexes r. Indexes s assigned to the sets <$R_x$, r, s> and relating to the sequence $(R_x, ...)_s$ of one initiation function $I_i$ (one vertex) form a set $S_i$. The number of different sequences is equal to the numerousness of a set $S_i$; indexes s assume values 1, 2, ..., Si (from left to right, clockwise rotation). Thus, the sequence $(R_x, ...)_s$ constitutes a set of these $R_x \in R'$ assigned by function $H_u$ to graph edges with a common end vertex and identical indexes 1 in the sets of <Rx, r, s>.

A part of the network corresponding to the sequences $(R_x, ...)_s$ is shown in Fig. 9. The initiation function $I_p$ is determined by the following formula:

$$I_p = (R_1, R_2)_1 \nabla (R_1', R_3)_2 \qquad (19)$$

The network of function N constructed in accordance with these principles allows to perform calculations and analysis of their correctness if their implementation will go in accordance with the appropriate axiom of Clearity, Feasibility and Compatibility (axiom system CFC). The calculation of the initiation function, the reaction function and control functions is carried out simultaneously across the network initialization function. The correctness of the calculations (according to the characterization principle: a functioning model $\Psi_a$) is determined by the correctness network topology (structural model $\Psi_b$) in the sense of axiom system CFC.

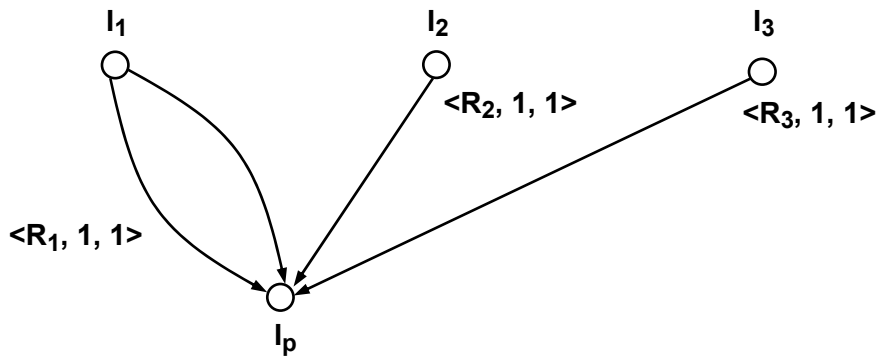


Figure 9. Example of the network fragment with the multiple edges and two sequences $<R_1, 1, 1>$ and $<R_1', 1, 2>$

## 10 Summary – the axioms of Clearity, Feasibility and Compatibility

Organizational–technical systems design can be carried out in many ways. This work presents considerations indicating the possibility of designing complex systems combining with simultaneous analysis of their functioning, carried out at the level of logical structure.

The principle of characterization belongs to the methodological apparatus of modern systems theory [4]. The main epistemological postulates of the characterization principle are as follows:

- characteristics of the solutions rather than the solutions themselves should be sought;
- solution characteristics should relate to the created class representatives (invariants) of equivalent solutions; and
- equivalent solutions class is created as a result of input data interpretation of the solved task group of the problem area in the representative solution characteristics categories.

Usually, there is less equivalent class solutions than the solutions themselves and the analysis of the characteristics of solutions can be carried out without their direct (objective) generation. Characterization theory consists of formal elaboration and methodological verification in the selected characterization theory objective area, which includes the basic idea of the mutual interpretability of functioning model to the model structure of certain object with the model of its structure. Mutual interpretability of models is achieved through:

- selection of universal rules of “proper” functioning (expressed in the functioning model) and
- structural (technical) interpretation of the functioning model.

The defining of axioms (and not just the rules) of the correct functioning (action) is the sine qua non of a satisfactory project design and the implementation of a system based on the project. The axioms allow constructing theories and theorems, and proving their completeness and consistency. Formulating rules may resemble, at the most, "patching" of the operating system or another system. It is impossible to effectively “patch up” loophole in the law or other legal act by using only rules, which are almost daily media reports.

The beginning of the road towards the correct project and its implementation is the correctness of the formal model. It is not possible to get the correct project if its model assumptions (functional and/or structural) are erroneous. The correctness of model, of course, does not imply automatically the correctness of project, but if the project has the characteristics of a formal model (and nothing else) and the producing operations are technologically correct, thus, in addition to a certain idealization, it is difficult to deny that approach. Hasse diagrams are examples of formally correct structures that can be automatically transferred and implemented in a physical medium. It is also important that the testing of the correctness of the Hasse logical structures is not necessary, as long as they have been obtained by using the theory of characterization.

The computation correctness on the **N** network depends on the structure of the network. Calculations on the network relate to the value of initiation, response and control functions.

The calculation of these functions will be called logically valid (valid in a logical sense) if they take place in accordance with the logical correctness of the axiomatic system specific for the network of **N** functions.

Axiomatic logical correctness is formed by:

- axiom of Clearity (C),
- axiom of Feasibility (F), and
- axiom of Compatibility (C).

Presented below axiom of extensionality, feasibility and compatibility (axiomatic CFC) is the result of the analytical work on multiple models of concurrent discrete processes, such as regular expression language [1, 11], machine scheme and operators [1, 3], a Petri net, transforming networks [10, 13, 14] and others.

### 10.1 Axiom of Clearity

Axiom of Clearity is formulated as follows:

> If there is in the formula $\nabla$ (R, ...) more than one sequence $(R_x, \ldots)_s$, the value 2 of any of these sequences can be converted into a value 1 only in the calculation for one sequence and other sequences should assume a value 0; time sequence of the changes in the sequence is not important. (20)

Axiom of Clearity establishes the need for natural uniqueness (within the network of structure N, for example, damping and inductive coupling or artificial synchronization (using additional elements outside of the network) of the changes in a value of 0 and 1 onto 2. Thus, the possibility of the so-called "race" performance of computing and related race of initiation operation and control-enforcement operations are blocked.

### 10.2 Axiom of Feasibility

Feasibility axiom is formulated as follows:

> Formulas $\nabla$ $(R_x, \ldots)$ must be constructed in such a way that during the calculation, starting from the initiation function $I_a = 1$ can be obtained for any one value $I_i \in I$ including the final operation initiation function $I_b$. (21)

This axiom requires that configurations and functions of the initiation sequence $(R_x, \ldots)_s$ should not occur in the structure of the network initialization function N because they could affect the suspension of computing operations, for example, due to the lack of changes in the value of individual response functions in accordance with the diagram $2 \leftrightarrow 0$ or $2 \leftrightarrow 1$, and at the same time the initiation functions for which the reaction functions are arguments. Feasibility axiom shows the need to ensure the achievement of value 1 by any function of the reaction occurring on the network N.

This axiom implies a potential need for the adoption of a value 1 by each initiation function, however, in a particular course of calculation from $I_a = 1$ to $l_b = 1$, not all the functions of initiation must be set to value 1.

### 10.3 Axiom of Compatibility

Axiom of Compatibility reads as follows:

> None of the functions $I_i \in I$, $R_x \in R$, $C_u \in C$ cannot change its value in other way than assigned by diagram $0 \leftrightarrow 2 \leftrightarrow 1$ (22)

Axiom of Compatibility blocks the formation of queue arguments and computing operations of initiation and response functions. The fulfillment of this axiom allows, consequently, observing the proper functioning of the network **N** of initiation function.

Axiom of Compatibility precludes the existence of value queues different from the background (which could arise, for example, as a result of the occurrence of cyclic zones in the network) and, to some extent, "organizes" (synchronizes) the arguments and computational operations of function $I_i$.

The synchronization effect of value changes is determined by appropriately defined computational rules that under certain conditions induce functions I, R and C, which take a value 2. Synchronization allows the alignment of "relative speed" changes in the reaction function $R_x$ which are arguments of one initiation function.

It is also assumed that the spread of a value 0 across network elements is at the "speed of light", i.e. immediately, regardless of the type of function (including the initiation and reaction function).

For practical reasons, the design of network N (the process) should weaken the functional limitations (expressed in a model $\Psi_a$) and structural constraints (expressed in a model $\Psi_b$). This issue will become more apparent after the presentation of some special properties of the N network (relationships on the network function). An axiom system CFC allows diagnosis of the so-called local and global correctness of the computation operations as well as the topologically error-free design of network function N.

The problem of the weakening of functional limitations and structural constraints requires a separate treatment because the solution is associated with the argumentation of many theorems about the completeness and consistency of primary assumptions of the original axiom **CFC**.

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