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IMPROVING MANUFACTURING PROCESSES USING SIMULATION METHODS

Abstract

The paper presents the results of simulation research on buffer space allocated in a flow line and operation times influence on the throughput of a manufacturing system. The production line in the study consists of four stages and is based on a real machining manufacturing system of a small production enterprise. Using Tecnomatix Plant Simulation software, a simulation model of the system was created and set of experiments was planned. Simulation experiments were prepared for different capacities of intermediate buffers located between manufacturing resources and operation times as input parameters, and the throughput per hour and average life span of products as the output.

1. INTRODUCTION

Computer simulation is a powerful method for designing and analyzing manufacturing processes in industry. Today, within a relatively short period of time, it is possible to design or redesign a manufacturing system to implement new production processes using simulation software. On the basis of the layout of a plant and a description of the technology in use, manufacturing resources can be allocated and the performance of the system can be estimated. A simulation model enables us to analyze various alternatives of the manufacturing system configuration and gauge the influence of the different parameters on the efficiency of different manufacturing processes. Advanced tools of computer simulation enable the analysis of the general performance of manufacturing systems, scheduling methods, support of facility layouts, automated material handling,

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automated guided vehicle systems design, etc. By doing this, we can reduce manufacturing costs and improve the system's throughput. Typically, however, the building of a simulation model of a manufacturing system is time-consuming and only enables the solution of individual problems. Therefore, it is often the case that a generalization of the results of simulation research is difficult. A very important advantage of a computer simulation is the possibility to create a model of a manufacturing system whose behavior could be very close to the real system. Modelling the processes of a manufacturing system and production processes is time-consuming and needs expert knowledge which increases the costs of the simulation method. To reduce the modelling time, often some simplifications of a manufacturing system are introduced which do not significantly affect the behavior of the system. Especially for companies which implement multi-assortment, repetitive production; it is very important to design and organize the production system effectively. Each new project requires the design of a technological process. To analyze the efficiency of a new production process, a model should be created that includes operation and setup times, the number of workers, the capacity of intermediate storage buffers, the availability of machines and tools, etc.

1.1. Literature overview

Simulation has been successfully implemented in a lot of research related to manufacturing system design and operation. Computer simulation offers very effective tools for visualizing, understating, and analyzing the dynamics of manufacturing systems (Seleima et al., 2012). Due to its complexity and importance, the buffer allocation problem has been studied widely and numerous publications are available in the literature. Stanley and Kim (2012) presented results of simulation experiments made for buffer allocations in closed serial-production lines. For the line, a single buffer space is the room and the associated material handling equipment that is needed to store a single job that is a work-in-process, and buffer allocation is the specific placement of a limited number of buffer spaces in a production line. The authors demonstrated a buffer allocation decomposition result for closed production lines, and also provided evidence that optimal buffer allocations in closed lines are less sensitive to bottleneck severity than in open production lines. The placement of buffers in a production line is an old and well-studied problem in industrial engineering research. Vergara and Kim (2009) proposed a new buffer placement method for serial production lines. The method is very efficient and uses information generated in a production line simulation whose conceptual representation of job flow and workstation interaction can be described with a network which aims to place buffers in order to maximize throughput. They compared the results of the new method against a method for buffer placement based on a genetic algorithm. Yamashita and Altiok (1998) proposed an algorithm for minimizing the total buffer allocation for a desired throughput in production lines with phase-type processing times.

They implemented a dynamic programming algorithm that uses a decomposition method to approximate the system throughput at every stage. Gurkan (2000) used a simulation-based optimization method to find optimal buffer allocations in tandem production lines where machines are subject to random breakdowns and repairs, and the product is fluid-type. He explored some of the functional properties of the throughput of such systems and derived recursive expressions to compute one-sided directional derivatives of throughput, from a single simulation run. Shi and Gershwin (2009) presented an effective algorithm for maximizing profits through buffer size optimization for production lines. They considered both buffer space cost and average inventory cost with distinct cost coefficients for different buffers. To solve the problem, a corresponding unconstrained problem was introduced and a nonlinear programming approach was adopted. Abu Qudeiri et al. (2008) used a genetic algorithm for studying the design of serial - parallel production line. They tried to find the nearest optimal design of a serial parallel production line that maximized production efficiency by optimizing buffer size between each pair of work stations, machine numbers in each of the work stations and machine types. Nahas et al. (2009) formulated a new optimal design problem of a parallel production line, where parallel machines and in-process buffers are included to achieve a greater production rate. The main objective was to maximize the production rate subject to a total cost constraint. Nourelfath et al. (2005) formulated a new problem of the optimal design of a series production line system, and developed an efficient heuristic approach to solve it. The problem was solved by developing and demonstrating a problem-specific system algorithm. Fernandes and Carmo-Silva (2011) presented a simulation study of the role of sequence-dependent set-up times in decision making at the order release level of a workload controlled make-to-order flow-shop. They indicated that the local strategy, which has been traditionally adopted in practice and in most of the studies dealing with sequence-dependent set-up times, does not always give the best results. Matta (2008) presented mathematical programming representations for the simulation-based optimization of buffer allocation in flow lines.

1.2. Problem specification

In this paper, a simulation method is used to analyze the impact of intermediate buffer capacities and lot sizes on the throughput of a production line. The buffer allocation problem is an NP-hard combinatorial optimization problem which deals with finding optimal buffer sizes to be allocated into buffer areas in a production line (Smith & Cruz, 2005; Huang, Chang & Chou, 2002). In general, the buffer allocation problem is classified into three categories according to its objective function (Demir et al., 2013; Krenczyk & Skolud, 2014):

1. Maximize the throughput rate of the production line with fixed amount of buffer sizes.
2. Minimize the total buffer size to achieve the desired throughput rate of the production line.
3. Minimize the average amount of work-in-process in the production line.

The presented paper takes into account the combination of the first two problems. The main problem considered in the paper can be formulated as follows: *Given a production line with a determined number of manufacturing resources, operation times and set-up times. How does an intermediate buffer capacity and sequence of operation times affect the throughput of the production line?* Using a simulation method, the best relation between allocated buffer capacity and throughput for several variants of operation times is examined. On the basis of the proposed simulation experiments, the principles by which solutions are reached can be analyzed and evaluated. In the next chapter, the simulation model of the production system is described and assumptions for simulation experiments are formulated. The third chapter contains the results of the simulation research and an analysis of the behaviour of the manufacturing system. In the last chapter, conclusions and directions for further study are presented.

2. SIMULATION MODEL OF THE MANUFACTURING SYSTEM

The model of the automated production line was prepared on the basis of a real example of a manufacturing system dedicated to metal tooling in an automotive company. The model and simulation experiments are implemented using Tecnomatix PLM simulation software. The studied manufacturing system includes four technological operations: cutting, turning, milling and grinding. The manufacturing process is divided into four stages by technology and between each two stages an intermediate buffer is allocated (Diering et al., 2015). Every stage of the manufacturing system encompasses a determined number of manufacturing resources (three CNC machines in every stage). The simulation model of the manufacturing system was prepared with Tecnomatic Plant Simulation Software version 11.0.0 and is presented in Fig. 1.
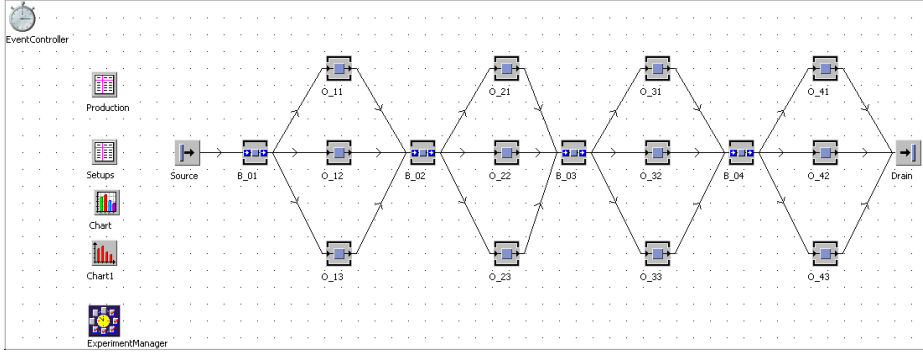
Fig. 1. Simulation model of the manufacturing system (own study)

The production is divided into four batch sizes of products (A, B, C, D) and realized cyclically. It was assumed that the efficiency of manufacturing resources is approximately 95%. The model of the production system was prepared on the basis of a real manufacturing company. The operation times are based on a lognormal distribution. A lognormal distribution is a continuous distribution in which a random number has a natural logarithm that corresponds to a normal distribution. The realizations are non-negative real numbers. The density of the lognormal distribution Lognor(σ,μ) is calculated as follows (Tecnomatix, 2011):

$$f(x) = \frac{1}{\sigma_0 x \sqrt{2\pi}} \cdot \exp\left[\frac{-\ln(x-\mu_0)^2}{2\sigma_0^2}\right] \tag{1}$$

where σ and μ are respectively mean and standard deviations and are defined as follows:

$$\mu = \exp\left[\mu_0 + \frac{\sigma_0}{2}\right] \tag{2}$$

$$\sigma^2 = \exp(2\mu_0 + \sigma_0^2) \cdot (\exp(\sigma_0^2) - 1) \tag{3}$$

The maximum of the density function is defined as:

$$\exp(\mu_0 - \sigma_0^2) \tag{4}$$

The example of the density function of lognormal distribution Lognormal(3,2) is presented in the Fig. 2 (Tecnomatix, 2011).

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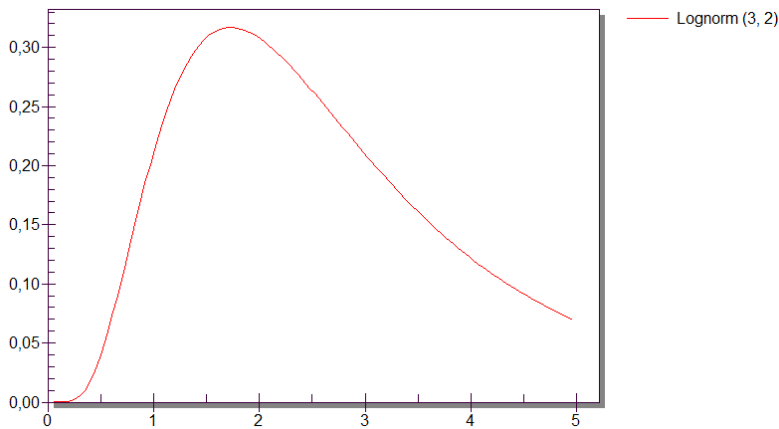
Fig. 2. Density function of lognormal distribution – lognor(3, 2) (own study)

The variants of operation times are presented in the table 1.

Tab. 1. The matrix of variants of operation times (own study)

Technological operations	Variant 1	Variant 2	Variant 3	Variant 4
O_11;O_12;O_13;	Lognor(5;0.5)	Lognor(5;0.5)	Lognor(2;0.5)	Lognor(5;0.5)
O_21; O_22; O_23;	Lognor(5;0.5)	Lognor(4;0.5)	Lognor(3;0.5)	Lognor(3;0.5)
O_31; O_32; O_33;	Lognor(5;0.5)	Lognor(3;0.5)	Lognor(4;0.5)	Lognor(3;0.5)
O_41; O_42; O_43;	Lognor(5;0.5)	Lognor(2;0.5)	Lognor(5;0.5)	Lognor(5;0.5)

The set-up times are defined in a set-up matrix (see Table 2). The numbers presented in the set-up matrix refer to the set-up time of changing the production batch (for example a batch change from product A to product B takes 15 minutes of set-up time).

Tab. 2. The matrix of setup times (own study)

	Product A	Product B	Product C	Product D
	10:00.0000	10:00.0000	10:00.0000	10:00.0000
Product A	10:00.0000	15:00.0000	10:00.0000	10:00.0000
Product B	15:00.0000	10:00.0000	20:00.0000	10:00.0000
Product C	20:00.0000	15:00.0000	10:00.0000	15:00.0000
Product D	10:00.0000	20:00.0000	20:00.0000	10:00.0000

The sequence of lot size is presented in the Table 3.

Tab. 3. The lot size matrix (own study)

	Lot size
Product A	20
Product B	25
Product C	15
Product D	10

The main variable in the simulation experiments was the intermediate buffer capacity. The proposed values of different combinations of intermediate buffers capacities that define the simulation experiments are presented in Table 4. The combination of the buffer capacities was chosen arbitrarily on the basis of author's experiences.

Tab. 4. The matrix of intermediate buffer capacities (own study)

Experiment	B_01	B_02	B_03	B_04
Exp 01	1	1	1	1
Exp 02	3	3	3	3
Exp 03	5	5	5	5
Exp 04	1	5	10	15
Exp 05	15	10	5	1
Exp 06	1	10	10	1
Exp 07	10	1	1	10
Exp 08	10	1	10	10
Exp 09	10	10	1	10
Exp 10	1	2	3	4
Exp 11	4	3	2	1
Exp 12	10	10	10	10
Exp 13	20	20	20	20
Exp 14	30	30	30	30
Exp 15	50	50	50	50

In addition to the system throughput per hour, the average life span of products in the manufacturing system was analyzed. The average life span shows us how long the products stay in the system and enables us to identify the level of work-in-process. In the next chapter, the results of the simulation experiments are presented.

3. THE OUTCOMES OF COMPUTER SIMULATION EXPERIMENTS

On the basis of the described simulation model, a set of simulation experiments for four variants of operation times, as presented in Table 1, were performed. The results of the simulation research show that, generally, the throughput of the system increases with increasing buffer capacities, but together with an associated increase in the average life span of products (work-in-process). To find the best compromise between throughput and average life span; flow index θ is proposed. To calculate the index, the value of the throughput of the system is divided by the average life span.

$$\theta = \frac{T}{\Lambda} \tag{5}$$

where T and Λ are throughput and average life span, respectively.

The results for the experiments are presented in table 5. In the table the best two results for each variants are shown.

Tab. 5. The values of flow index (own study)

	Variant 1	Variant 2	Variant 3	Variant 4
Exp 01	292.72	406.41	331.13	325.94
Exp 02	274.34	381.21	306.11	307.76
Exp 03	285.29	408.47	309.32	319.48
Exp 04	**376.26**	**523.72**	**349.84**	**403.30**
Exp 05	152.47	219.94	166.36	176.27
Exp 06	237.57	394.16	244.18	270.17
Exp 07	210.33	270.68	259.81	244.23
Exp 08	254.46	317.09	310.49	283.30
Exp 09	215.25	293.25	258.38	271.26
Exp 10	**321.87**	**450.00**	**364.99**	**360.03**
Exp 11	239.01	331.22	266.83	267.57
Exp 12	281.30	388.26	259.62	290.60
Exp 13	214.48	299.08	145.01	226.58
Exp 14	175.32	241.21	99.99	191.72
Exp 15	136.87	174.05	62.30	146.69

The greater the value of the index, the better the compromise between the throughput and average life span that can be found. The best values of the flow indexes were obtained in Variant 2 of the operation times. For experiments 4 and 10, the best values of the index are obtained. The chart presented in Fig. 3 show the values of the flow indexes for all variants of operation times.
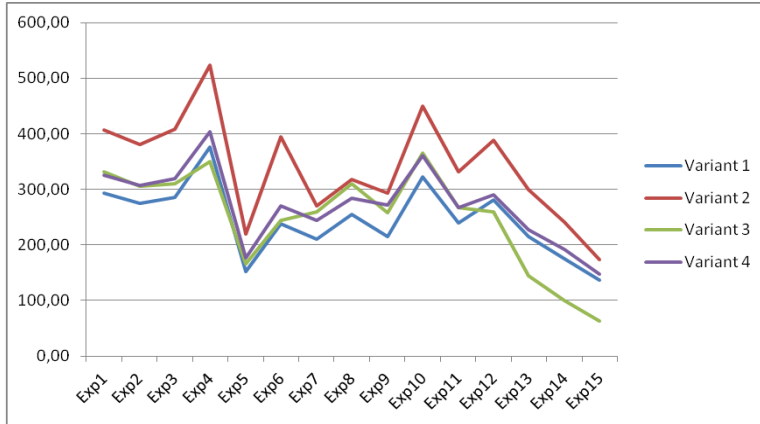
Fig. 3. The values of flow indexes for the different variants of operation times (own study)

The increase in the intermediate buffer capacities results in an increased average life span and work-in-process. The buffer capacity costs money (place, work-in-process, etc.). To comply with the capacity of the intermediate buffers in the analysis of the efficiency of the investigated manufacturing system, the total buffer productivity index ω is proposed.

$$\omega = \frac{T}{B} \qquad (6)$$

where T and B are throughput and total buffer capacity, respectively.

In Fig. 4, the total buffer productivity indexes for all variants are presented. There are no significant differences among the values of buffer productivity indexes measured for the various variants. The greatest value in the index was obtained in experiment 1, and it resulted from the small value of the total buffer capacity (single capacity of intermediate buffers). The next best relation between the throughput and buffer capacity for all variants was obtained in experiments 10 and 11.

4. CONCLUSIONS

An analysis of the data collected during the simulation experiments shows us that for each variant of the operation times, in the last four experiments (12, 13, 14 and 15) in which all buffer capacities are equal or greater than 10, the throughput of the manufacturing systems achieved the best results (more than 22 products per hour). For the smallest total capacity of intermediate buffers, the greatest value of throughput was reached in experiments 4, 6, 8 and 9. For flow index, experiments 4, 6 and 10 provided very good results, and for buffer productivity index: experiments 1, 10 and 11. For the manufacturing system, which was investigated in this study, the following general conclusions can be formulated:
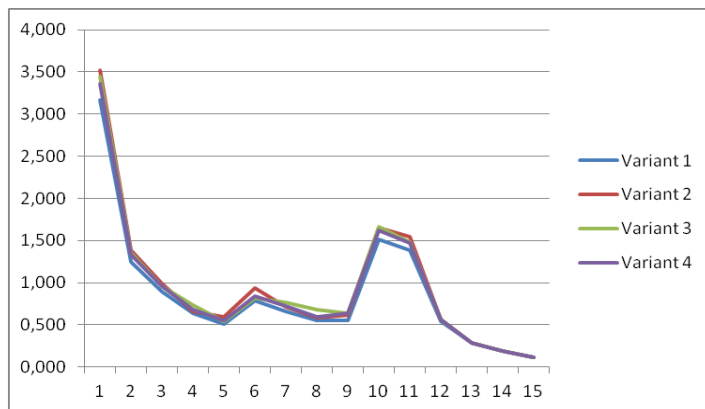
Fig. 4. The values of total buffer productivity indexes
for the different variants of operation times (own study)

- The intermediate buffer capacity has a significant impact on the throughput and average life span of the system.
- The proper allocation of buffer capacities provides better values of throughput or average life span of the system.
- It is possible to find a satisfactory compromise between the throughput and average life span of the system, maximizing the proposed flow index.
- It is possible to find a satisfactory compromise between the throughput and costs of buffer capacities, maximizing the proposed total buffer productivity index.

Further research will encompass other structures of the manufacturing system and the impact of employees on the throughput of the manufacturing system.

REFERENCES

Demir, L., Tunali, S., Eliiyi, D. T., & Lokketangen, A. (2013). Two approaches for solving the buffer allocation problem in unreliable production lines. *Computers & Operations Research, 40*(10), 2556-2563. doi:10.1016/j.cor.2013.02.004

Diering, M., Dyczkowski, K., & Hamrol, A. (2015). New Method for Assessment of Raters Agreement Based on Fuzzy Similarity. *10th International Conference on Soft Computing Models in Industrial and Environmental Applications, 368*, 415-425. doi:10.1007/978-3-319-19719-7_36

Fernandes, N. O., & Carmo-Silva, S. (2011). Order release in a workload controlled flow-shop with sequence-dependent set-up times. *International Journal of Production Research, 49*(8), 2443-2454. doi:10.1080/00207541003720376

Gurkan, G. (2000). Simulation optimization of buffer allocations in production lines with unreliable machines. *Annals of Operations Research, 93*, 177-216. doi:10.1023/a:1018900729338

Huang, M. G., Chang, P. L., & Chou, Y. C. (2002). Buffer allocation in flow-shop-type production systems with general arrival and service patterns. *Computers & Operations Research, 29*(2), 103-121. doi:10.1016/s0305-0548(00)00060-5

Krenczyk, D., & Skolud, B. (2014). Transient States of Cyclic Production Planning and Control. *Engineering Solutions and Technologies in Manufacturing, 657*, 961-965. doi:10.4028/www.scientific.net/AMM.657.961

Smith, J. M., & Cruz, F. R. B. (2005). The buffer allocation problem for general finite buffer queueing networks. *Iie Transactions, 37*(4), 343-365. doi:10.1080/07408170590916986

Matta, A. (2008). Simulation optimization with mathematical programming repre-sentation of discrete event systems. In: *Proceedings of the 2008 Winter Simulation Conference* (pp. 1393-400). Institute of Electrical and Electronics Engineers, Inc. doi:10.1109/WSC.2008.4736215

Nahas, N., Nourelfath, M., & Ait-Kadi, D. (2009). Selecting machines and buffers in unreliable series-parallel production lines. *International Journal of Production Research, 47*(14), 3741–3774. doi:10.1080/00207540701806883

Nourelfath, M., Nahas, N., & Ait-Kadi, D. (2005). Optimal design of series production lines with unreliable machines and finite buffers. *Journal of Quality in Maintenance Engineering*, *11*(2), 121-138. doi: 10.1108/13552510510601348

Abu Qudeiri, J., Yamamoto, H., Ramli, R., & Jamali, A. (2008). Genetic algorithm for buffer size and work station capacity in serial-parallel production lines. *Artificial Life and Robotics, 12*(1-2), 102-106. doi:10.1007/s10015-007-0449-5

Seleim, A., Azab, A., & AlGeddawy, T. (2012). Simulation Methods for Changeable Manufacturing. *45th Cirp Conference on Manufacturing Systems 2012, 3*, 179-184. doi:10.1016/j.procir.2012.07.032

Shi, C., & Gershwin, S. B. (2009). An efficient buffer design algorithm for production line profit maximization. *International Journal of Production Economics, 122*(2), 725-740. doi:10.1016/j.ijpe.2009.06.040

Staley, D. R., & Kim, D. S. (2012). Experimental results for the allocation of buffers in closed serial production lines. *International Journal of Production Economics, 137*(2), 284-291. doi:10.1016/j.ijpe.2012.02.011

Tecnomatix Plant Simulation version 11.0.0, on-line documentation, 2011.

Vergara, H. A., & Kim, D. S. (2009). A new method for the placement of buffers in serial production lines. *International Journal of Production Research, 47*(16), 4437-4456. doi:10.1080/00207540801939022

Yamashita, H., & Altiok, T. (1998). Buffer capacity allocation for a desired throughput in production lines. *IIE Transactions, 30*(10), 883-891. doi:10.1080/07408179808966542

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ON-THE-FLY COMMUNITY-DRIVEN MOBILE ACCELEROMETER DATA ANALYSIS SYSTEM FOR ROAD QUALITY ASSESSMENT

Abstract

In this paper the authors are discussing a community-driven system for reporting via smartphones road acceleration data, processed on-the-fly in the cloud computing system for finding possible road artefacts as well as assessing overall road quality on the driver-friendly RRUI scale. The proposed system uses smartphones mounted in a car with little to no calibration or initial setup. By performing a fast analysis in the cloud, data are made immediately available for other users. The system continuously sends to end users' devices data about road quality issues "in exchange" for acceleration information.

1. INTRODUCTION

Road conditions affect road users in different ways: fuel efficiency, vehicle and driver fatigue, and user comfort. Published data about the state of roads may be used to optimize traffic, but also in professional transport, for example chassis configuration for trucks (Lundstrom, 2009). The negative impact

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of different types of road artefacts – potholes, speed bumps and similar is also important (Badurowicz & Montusiewicz, 2015). Information about road condition is also a crucial factor in decisions as to which roads should undergo maintenance in the next round and how they degrade with time, important for sparsely populated regions.

There are currently discussed standards on reporting road surface profiles – in the Polish law system there is an instruction provided (Duda & Adamczyk, 1999) for assessment of the technical quality of the road, which must be provided by the road operator for preparing strategic plans of improving road quality, while assessment is provided by a group of experts using paper protocols, rather than automatically, while better methods using current technology were proposed by Gajewski (2013). This kind of methods, while useful for road operators, experts and governmental units, are however not so useful for average road users, as they require additional knowledge to be properly analyzed, and as this kind of data is usually not publicly distributed to road users on demand. It is also impossible for expert groups to continuously monitor road quality on a vast area of the country.

The authors propose the use of smartphones mounted in road users' cars for basic road quality monitoring. Smartphones are much more prevalent than any kind of specialized equipment, they have a variety of built-in sensors and communication units. Based on this, the authors propose a crowdsourcing project using personal smartphones to record accelerometer data for road quality assessment.

2. DESIGN AND MOTIVATIONS

The general idea is based on the road artefact detection concept the authors proposed in earlier works (Badurowicz & Montusiewicz, 2015). In this paper, the authors concentrate on streaming analysis of data coming from road users' devices.

The key concept of the proposed solution is to use road users' smartphones mounted in their cars in a way that the device can record acceleration data of the car. This means the device has to be mounted in a stable hold, and it is the only requirement: device orientation however is not important, as the authors are using an orientation-agnostic way of acceleration data recording by means of a rotation matrix calculated from the array of the device's sensors. This means that little to no calibration is required for the end user to use the system. The main sensor device used is the accelerometer, which reacts to shakes from the road surface, going through all the car's parts. Taking into account the results of all the previously performed experiments, which used different cars from different manufacturers and in a different overall state, there is always a direct connection between data recorded by the accelerometer and road profile (Badurowicz & Montusiewicz, 2015; Astartita et al., 2014).

The current solution is acquiring data on acceleration in all three axes, acceleration data after rotation matrix transformation, current location, speed, course, time (synchronized with Network Time Protocol server) and GPS (Global Positioning System) accuracy. Data from many devices, which is actually data from multiple cars, are processed in the cloud-computing system in streaming analysis fashion. To achieve communication between the devices and the computing system, the MQTT protocol is used.

The authors are performing different kinds of analysis on the data received by the system, where one of the key factors of road quality estimation is to examine the quantity and intensity of road artefacts - various kinds of potholes, road surface damages and similar, as well as the overall state of the road, which is information taken directly from the statistical analysis of the collected signals.

As similar techniques for using accelerometers for International Roughness Index calculation were previously used in (Du & Lin & Wu & Jiang, 2014) and (Hanson et al., 2014), the authors believe that end users, to whom the system will be offered, need more user-friendly ways of calculating road quality than professionals, and a simple scale allowing for quick understanding while driving. The concept of a social system for road defect detection was previously suggested by Aksamit and Szmechta (2011), however in the present authors' solution there is a significant difference – data are not only being analyzed in stream analytics fashion in the cloud computing system, but the resulting information is also being sent back to the device. Also, the whole concept of road condition monitoring was also discussed earlier (Chen at el, 2011), however in the authors' proposal the sending and receiving device is just the simple smartphone, with everything integrated in the software, not relying on external sensors.

3. PRINCIPLES OF ON-THE-FLY DATA ANALYSIS

The data obtained from the mobile devices produce a continuous stream. Hence, the amount of information grows over time. Not every event produced by the mobile sensors is important but each one must be analyzed. The number of mobile devices included in the system is not limited, so the amount of events passing through the system is difficult to predict. Making such assumptions, the overall system can be described with two models: as Big Data and as the Internet of Things.

In general, there are two main models for big data computing. The first one is big data batch computing (BDBC), where the flagship solution is Hadoop. The second model is called big data stream computing (BDSC) (Sun & Zhang & Zheng & Li, 2015). In the case of BDSC, the straight-through computing model has implementations in such systems as: Apache Storm, S4, Akka and IBM InfoSphere Streams. In contrast to batch computing, where the data are first stored and then computed,

stream computing is sufficient for many real-time application scenarios, where the result must be updated every time the data change. In the case of the real-time applications where the input stream incurs multistaged computing, stream computing ensures low latency to produce an output stream (Hummer & Satzger & Dustdar, 2013).

A continuous data stream is an infinite sequence of data sets, and parallel streams produce more than one stream at the same time. A big data input stream has the characteristics of high speed, real time, and large volume for applications, like the system described here.

In an endless stream of data, the data flow can be partitioned into subgroups, called windows. Depending on the solution, a number of types of windows can be distinguished. Each window has a start condition and an end condition. The basic type of query window is the growing window which binds data values to be available over the entire stream. In contrast, the single item window is where each single event is considered separately. The third type is the tumbling window, where a new window is created if there is currently no other open window. The tumbling window fills with data, performs whatever operator is specified, and then moves to an entirely new window of data. It tumbles forward trough the data, end over end. The next type of window is the sliding window, where it fills with its first subgrouping of data, performs whatever it is an element of, then continues with these same data, adding them incrementally, or sliding, as new data are received. The last type of window is a landmark window query, where once a window is opened, it remains open indefinitely. In contrast to the growing window which binds some values over the entire stream, the landmark window considers different portions of the stream over time. The stream data can be promoted into windows by defining a number of conditions, such as row count, elapsed time or marker in the stream.

4. ROAD QUALITY ESTIMATION FROM ACCELERATION DATA

To evaluate the quality of the road travelled an accelerometer was used, located inside a conventional mobile device, i.e. a smartphone. This examination of the quality of the road leads indirectly to determining the comfort of driving along this road.

The application for the smartphone collects the data indicating acceleration in the global coordinate system associated with the current sample time and the current location from the GPS system. In the experiment we used constant sampling frequency of 10~Hz. This value was chosen on the basis of the ana-lysis of the speed of the vehicle on the roads of various types and after conducting preliminary studies. Moving on the road of bad quality was possible at speeds not exceeding 30 km/h, and on seeing the different types of road damage, e.g. potholes, the driver had to perform a braking maneuver and, if possible, a partial bypass.

In such situations, the vehicle speed was reduced to about 10-20 km/h. On the application of sampling it was possible to record waypoints distant from each other about 28 to 85 cm. While driving along the city's ring road, the car reached the speed of about 90 km/h – the obtained sample corresponded so sections of the road at 250 cm. Preliminary studies have confirmed that on roads in very good condition there is no need to collect information at a higher sampling rate, since there are no artefacts that should be noted.

The developed road test methodology included the following activities:
- choice of appropriate sections of the road for the research,
- road of very good quality (Lublin ring road),
- a gravel road (Snopków village near Lublin),
- paved road - so-called cobblestones (Lublin, Agronomiczna Street).
- a test drive along the route, verification of its state,
- selection of software parameters for the registration of the road's condition,
- sending the data to the computer cloud.

For the purpose of getting information of interest to end users, the authors decided to perform road artefacts (potholes, speed bumps, road surface quality changes) detection from a data stream, by using the streaming computing method. The artefacts are "deviant" points in the Z-axis acceleration data stream. To find those points a design pattern called "outlier detection" was applied (Ballard et al., 2012). The computing solution was built by applying the IBM Infosphere Streams system. The aim of the solution is to forward only those tuples (data points) that are considered outliers. The outliers are identified by computing the distance of a data value from a mean. The mean is calculated over a sliding window the size of 25 tuples.

The algorithm considers a data point as an outlier when the Z-axis acceleration value is higher or lower than the sum of the average value of Z-axis acceleration and the product of standard deviation of the Z-axis acceleration value multiplied by sigma. The value of sigma was established experimentally and equals 2.25 in the case of the present research. The average value and standard deviation of the Z-axis acceleration were calculated by using functions provided by the Aggregate operator (see Fig. 1-B). The Aggregate operator is a part of stream the diagram depicted in Figure 1.
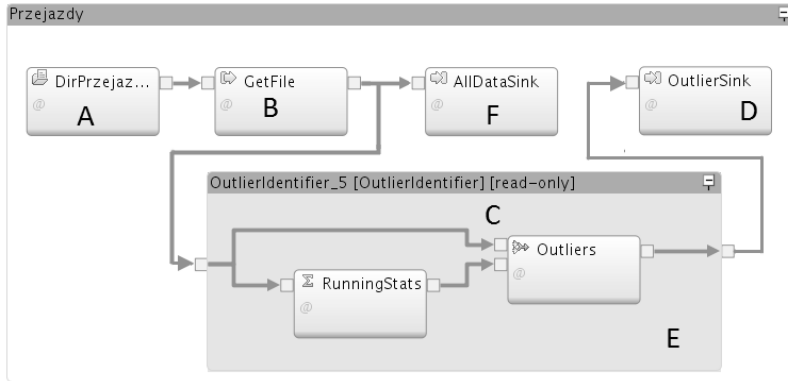
Fig. 1. Stream graph representing the system for outlier detection (own study)

The ingest of the stream consumes all the data from the input port – the input port of the whole system is built upon the MQTT source operator (see Fig. 1-A). It connects with the MQTT broker and receives information produced by the device placed in the car. Then data flows into the OutlierIdentifier operator (see Fig. 1-E) as well as into the AllDataSink operator (see Fig. 1-F). The latter is used just for debugging purposes, to accumulate all the data received from the MQTT source.

In the OulierIdentifier operator the stream is divided into two substreams. The first one goes into the input port of the Aggregate operator where the mean and standard deviation are computed. The outcome of the Aggregate operator produces a substream with tuples described by the schema depicted in Figure 2.

Fig. 2. Data scheme of the outcome of Aggregate operator (own study)

To get the outliers, both streams – all the data and substream received from the Aggregate operator – must be merged into one, containing only outlier tuples. To achieve this, the Join operator was used (see Fig. 1-C). Join operator contains the isOutlier function (see Listing 1). The isOutlier function computes the Z-axis acceleration distance from the mean. If it returns true, the data is an outlier and is forwarded to the output. Then outliers are placed in the OutlierSink (see Fig. 1-D).

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5. EXPERIMENTAL RESULTS

All data received from mobile devices were analyzed but only three types of roads are going to be shown in this part of the article. To clarify the explanation in Figure 3 only four seconds of the test drive are shown. On the X-axis the time in unix timestamp format is presented, the Y-axis depicts the acceleration. Standard deviation was computed in two ways: the first one was obtained over all data of the research sample – the sample contains 5008 measuring points. In this case the standard deviations equals 0.2003. The second way of standard deviation calculation was done during streaming analysis. It is not a constant in time, but depends on calculation in a window and changes acceleration value along the Z-axis. Every new tuple coming into the window removes the oldest one and at that time a new value of the mean and standard deviation are produced.

In Figure 3 the data points received from the research are marked as grey stars, constant deviation is marked as a Y bar error and standard deviation computed over the window is marked as a black line with triangle marks. The output of the streaming analysis – outlier data – is marked as black dots. When the road quality decreases the slope of the window, the calculated standard deviation line increases.
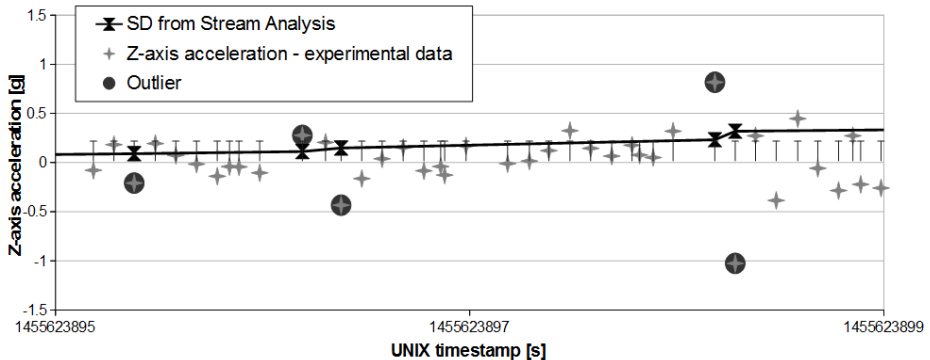
**Fig. 3. Measurements of data quality represented by Z-axis acceleration
vs. time for a gravel road (own study)**

On the following three figures outliners are going to be shown for three different types of roads. To simplify the observation only outliers are depicted on the graph. The time duration for each graph equals 100 s. Thereby, the number of measurements points equals 1000.

In the case of very good road quality (see Fig. 4) only a small number (14 points) of outliers was found. The acceleration value over the Z-axis is close to zero and the value of the outliers does not even exceed 0.5g.
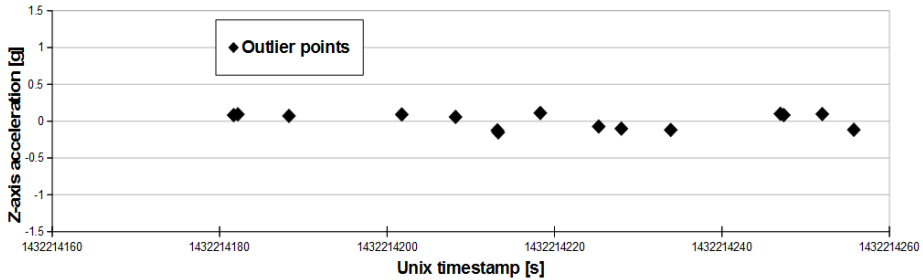
Fig. 4. Outlier points for a road of very good quality (own study)

With deterioration in the quality of the road surface in the case of a paved road – so-called cobblestones (see Fig. 5), the number of outliers increases and reaches 31 points. At the same time the value of Z-axis acceleration increases, and in some points surpasses the value of 0.5g.
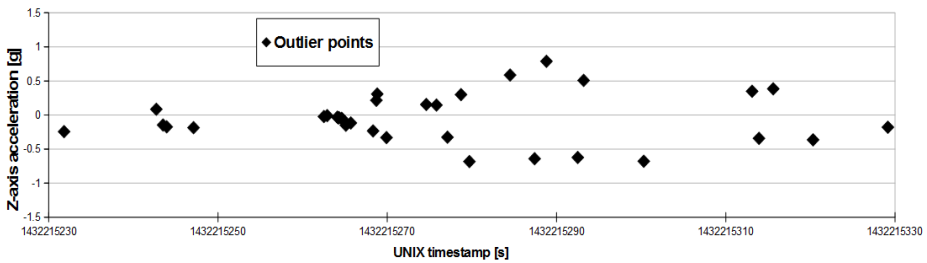
Fig. 5. Outlier points for a paved road – so-called cobblestones road (own study)

In Figure 6 the worst road surface examined is shown. Compared to the previous two samples, the gravel road presented here is characterized by a high number relative to the paved road, of the outlier points (49 of them). With a higher number of distinguished outlier points, their value of Z-axis acceleration exceeds the value of 1.0 g.
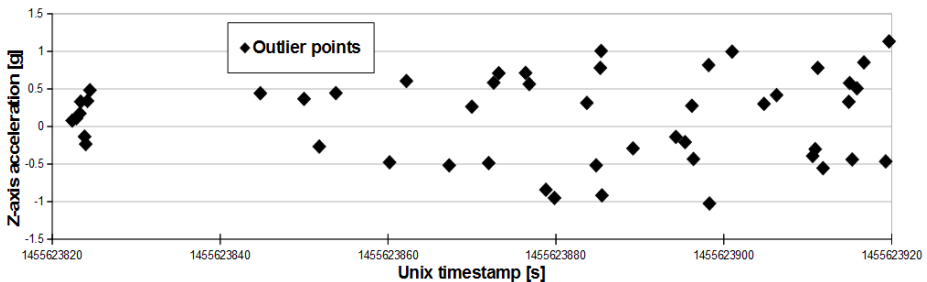
Fig. 6. Outlier points for gravel road (own study)

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5.1. The assessment scale

While the position of individual road artefacts is important for the driver, the overall state of the road is also a must. Therefore, a road classification may be proposed, similar to the one presented by Turkay and Akcay (2015) – the same road classes from A-H will be used, where A is a high quality road and H is the lowest quality (terribly poor) road, but the value will be based on standard deviation of Z-axis acceleration. Both the A and H class roads were tested experimentally, and the authors will use the A road standard deviation on the Z axis as the baseline for any other kind of road, using the formula:

$$RRUI = (\sigma_Z - A) \cdot 10^2 \qquad (1)$$

The RRUI, or Road Relative Unevenness Index, is calculated as the differrence between the standard deviation of acceleration in vertical axis from the road fragment being assessed (σ_Z) and the average standard deviation of an A-class road (Lublin ring road) (A), multiplied by 100 to achieve more readability. Based on streaming analysis principles, the authors asses not whole roads, but their fragments which are in one sliding window of the cloud computing analysis.

The gravel and paved roads acceleration data were statistically analyzed in the second stream analytics system, this time built by using the Tumbling Window technique on Microsoft Azure platform, again with the window size of 25 tuples. The values calculated from the first road are presented in the table 1, below:

Tab. 1. Calculated statistic values from Z-axis and RRUI for a road fragment (source: own study)

Fragment	Average acceleration	Standard deviation	RRUI value
1	-0.02529	0.062724	1.748547
2	-0.01818	0.057316	1.207696
3	-0.01836	0.045599	0.036032
4	-0.01305	0.058717	1.34784
5	-0.02467	0.050069	0.483021
6	-0.01938	0.191661	14.64223
7	-0.02452	0.166082	12.08434

The calculated RRUI is 14.64 at its highest. The same analysis was performed for the gravel road and the RRUI was up to the value of 45.03.

The proposed scale may be directly transformed into A-H alphabetic scale, allows end users to quickly assess road fragments directly ahead of them,

when the feedback information is being sent to their devices. The outlier detection finding hazardous road artefacts, on the other hand, warns users about dangerous places and advises them to slow down.

6. CONCULUSIONS AND FUTURE WORK

The authors performed streaming analytics, on-the-fly and without human intervention, of road acceleration data for finding different types of road artefacts and for assessment of road quality. This information is being sent to end-user devices who are participating in the social system, so in exchange for the road acceleration data they are being warned about incoming road quality issues.

The proposed RRUI scale is not the defining index of the road quality – there is a need for preparing a multi-factor road assessment, using the overall road quality from the RRUI scale, but also density and factor of the road artefacts found, and the creation of this kind of scale, useful for end users, will be the authors' target in the future.

REFERENCES

Aksamit, P., Szmechta, M. (2011). Distributed, mobile, social system for road surface defects detection. In: *Computational Intelligence and Intelligent Informatics (ISCIII)* (pp. 37-40).

Astarita, V., Vaiana, R., Iueleand, T., Maria, V.C., Giofre, V.P., Masi, F.D. (2014). Automated sensing system for monitoring of road surface quality by mobile devices. *Procedia - Social and Behavioral Sciences 111*, 242-251.

Badurowicz, M., Montusiewicz, J. (2015) Identifying road artefacts with mobile devices. *Information and Software Technologies, vol. 538*, Springer

Ballard, C., et al. (2012). *IBM InfoSphere Streams: Assembling Continuous Insight in the Information Revolution*. IBM Redbooks.

Chen, K., Lu, M., Fan, X., Wei, M., Wu, J. (2011). Road condition monitoring using on-board three-axis accelerometer and gps sensor. In: *Communications and Networking in China (CHINACOM)* (pp. 1032-1037).

Du, Y., Liu, C., Wu, D., Jiang, S. (2014). Measurement of international roughness index by using z-axis accelerometers and gps. *Mathematical Problems in Engineering 2014*

Duda, J., Adamczyk, M. (1999). *Instrukcja oceny stanu nawierzchni dróg publicznych w miastach*. Generalna Dyrekcja Dróg Publicznych

Gajewski, W. (2013). Nowoczesne metody diagnostyki stanu, czyli profilaktyka w drogownictwie. *Magazyn Autostrady Nr 10*, pp. 46-51.

Hanson, T., Cameron, C., Hildebrand, E. (2014). Evaluation of low-cost consumer-level mobile phone technology for measuring international roughness index (iri) values. *Canadian Journal of Civil Engineering 41(9)* (pp. 819-827)

Hummer, W., Satzger, B., Dustdar, S. (2013). Elastic stream processing in the cloud. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery 3(5)* (pp. 333-345)

Lundström, J. (2009). Road roughness etimation using available vehicle sensors

Sun, D., Zhang, G., Zheng, W., Li, K. (2015). Key technologies for big data stream computing

Turkay, S., Akcay, H. (2015). Spectral modeling of longitudinal road profiles. In: *2015 IEEE 28th Canadian Conference on Electrical and Computer Engineering (CCECE)* (pp. 477-482)

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MENTALLY CHALLENGED
AS DESIGN PRINCIPLES AND MODELS
FOR THEIR APPLICATIONS

Abstract

Tablet computers have become a common part of our life style. Since 2012, inspired by the success of touch devices in special education, we have established and led the IT therapy program for the mentally challenged. In this paper we also present one of our final study with 12 participants. Based on our findings from our studies we have finally proposed 14 design principles (an extension and redefinition of a previously proposed 10 simple design principles) which should be generally respected in design and development of every "usable/accessible" application for the mentally challenged. Some of these principles are applicable as design patterns or models in software development and some were already implemented in our framework which we used to develop new more usable applications.

1. INTRODUCTION

In last five years we have witnessed huge expansion of touch screen devices in our common life style. Beside touch smart phones, tablet computers are also emerging and have become the common part of our everyday technology. One of tablet computer emerging area is the branch of special education. In this area tablet computers have quickly become the part of assistive and education techno-logy. Thanks to a massive usage of touch technology in this area, the usage of tablet computers in special education is called "*the revolution of special pedagogy*", see (Rihova, 2013; Rihova & Jelinkova, 2013; Shah, 2011).

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Based on the success of these touch devices achieved in special education, we started a research project called "*computer therapy*" in 2012. One of the first main aims was to investigate and also offer the advantages of touch devices designs for daily life (outside the school walls) of mentally challenged individuals by creating a therapy like program with use of touch devices and applications. But as we started we figured out that there are many uncovered usability and accessibility issues even on existing, working applications used on touch devices in special education needs (SEN). Consequently we have pointed out that in order to be able to solve these issues we need multi-disciplinary approach, not only separated health, social, pedagogical, or IT approach. Hence on the turn of 2012/2013 we proposed first simple design principles based on our computer therapy project approach. These principles define how software (SW) should be designed, developed and deployed (used in practice) to bring maximal outcome in therapy for the mentally disabled.

Our therapy program was managed by corresponding author personally (7 hours per working day) in Czech home for mentally disabled. As part of this therapy we have conducted a series of long-term studies based on usability testing. During all three years more than 30 mentally challenged individuals have participated directly and another 10 indirectly in this long-term study. With respect to the scope of this long-term study, here we present one of our final sub-study with 12 participants.

Moreover we have also designed, developed and deployed new applications for the mentally disabled according to proposed design principles and their domain models (applying the model driven engineering methodology – MDE). These developed applications were consequently tested in our therapy environment of mentally challenged and the first positive results were already published in international journals and conferences (Fiala & Koci, 2014, 2015; Vejtasa, 2014).

In this paper, we first present a detailed description of later conducted usability testing and consequently we present the identified flaws of present day tablet computer app designs. Subsequently, based on these flaws, we recall proposed design principles which have been previously presented in a simplified version. The main content of this paper presents the extension and revision of these design principles (some also applicable as design patterns) and, furthermore, we demonstrate (see below our MDE development demo example) the way these principles can handle some of the identified flaws.

Although we operate here with some methods of human computer interaction, these methods are only auxiliary and the main contribution of this paper is in the scope of software engineering (where the proposed design principles have its place). Mentally disabled users are in the centre of our research, thus it is clear to call this summary of present research as "*Mentally challenged as design principles and models for their applications*".

1.1. Definitions

In our research "*computer therapy*" (abbreviated as *i-CT*) stands for research in software engineering and HCI which leads to a proposal of design principles, models for a development of applications for mentally disabled. Moreover, it stands for the therapy-like program (based on special education therapy) established for usability testing of developed apps (according to these principles). In our "*i-CT*" abbreviation, the letter *i* denotes the reference to an intelligent and intuitive touch device like iPad, *C* stands for computer and *T* for therapy term.

The human computer interaction metrics like usability, accessibility, usefulness, etc. are understood in terms of Nielson definitions (Nielsen, 1994). Other abbreviations like UML or MDE (model driven engineering), OCL (object constraint language) are standard terms used in software engineering.

1.2. Related Work and Research Bases

In spite of a wide scope of present research in human computer interaction, there still exists practical usability issues (e.g. section 3.1), or (Budiu & Nielsen, 2011; Fiala & Koci, 2014; Nielsen & Budiu, 2013) which should be discussed and handled. This also holds for the specific HCI area focused on SEN. One of the possible solutions is the proposed "*guideline*" for design and development in order to avoid inappropriate usability issues as a result. This can also be achieved by proposal of specific design principles.

The need and merits of design principles in the role of "*guideline*" for proper design and development is generally known and respected. Besides general software engineering design principles e.g. GRASP or SOLID in (Larman, 2005; Martin, 2000; Marinescu & Lanza, 2006) there is also the need of more specific design principles in specific fields. In the specific field of HCI the usage and benefits of design principles have also been proposed and discussed (Burgstahler, 2008; Karwowski, Soares & Stanton, 2011). Naturally, most of these HCI design principles are oriented on user interface (UI) which is the key part in human computer interaction (Pearson, Buchanan, & Thimbleby, 2010; Stephanidis, 2009).

In relation to the interaction with the disabled, there also appeared attempts to propose design principles for disabled individuals in the past. But before the boom of tablet computers (Hager, 2010; Shah, 2011), most of them were focused on interaction with classical PC or specific devices, see (Vanderheiden & Jordan, 2006). After the boom of touch devices in 2010, there appeared more works discussing the design principles focused on touch screen platforms but these were more oriented on intellectually capable individuals (Budiu & Nielsen, 2011; Pearson, Buchanan, & Thimbleby, 2010). On the other hand new research outcomes focused on design principles for interaction of the disabled

with a tablet computer were also proposed in previous years. In these contributions we mostly find works oriented on specific subgroup of disabled users for example autism (Signore, Balasi, & Yuan, 2014) or oriented on a very general group of disabled users in an effort to handle most of disabilities (Buhler & Pelka, 2014) or focused on design principles for one specific app for example in (Dobosz, Dobosz, & Fiolka, 2014; Signore, Balasi, & Yuan, 2014).

Beside the benefits of these efforts we understand the need of their further extension which is naturally invoked by daily needs of the mentally disabled (mostly observable in special education/therapy). Thus we put the mentally challenged individuals as the centre of our research. This leads us to specific conditions which should be met in the proposed design principles.

In comparison, the primary focus in our case is not only oriented on user interface (UI), but is closer to classical software engineering design principles. Although all of proposed principles are not primarily addressing UI, it finally has a fundamental impact to end-user usability and accessibility. In this research we come from our critical review of existing apps, from conducted long term usability testing and identified flaws. These flaws highlights the fact, that some of uncovered usability issues have its cause in inappropriate basic software engineering design and development. Therefore inappropriate basic software engineering design and development can have a fundamental influence on final app usability. As a result, our research basis puts some research specific constraints, which requires that all research criteria should be met. As we can recognise from related work discussion, our practical oriented research goals lead us to following specific criteria on design principles:

- Design principles are oriented on usability (HCI) issues (humans are in the centre of design), but are not strictly focused on UI elements.
- End-users are specifically mentally challenged individuals, but cover a wide range of mental disabilities with combined, attached impairments.
- Design principles are not focused on one group of specific apps design (e.g. apps for alternative and augmentative communication – AAC), but cover a range of common apps used in special education/therapy.
- Instead of PC platform, design principles are oriented on apps for platforms of touch devices (tablet computers and smart phones, multiplatform).
- Design principles are not defined as general plain text claims only, but in spite of its generality can be applied in real specific situations and can be represented formally by model representations (e.g. in UML with extension of OCL), which is common in SW design and development, e.g. see (Jacobson, Booch, & Rumbaugh, 1999).

These 5 research criteria create very specific conditions in our research. On the other hand, the need of "*guideline*" (e.g. represented by design principles) for special education is growing rapidly with growing success of touch, mobile

devices in this area which led to "*the revolution of special education*" in 2012, see (Rihova, 2013; Rihova & Jelinkova, 2013; Shah, 2011). Although such design principles may look very specific, they stand for "*guideline*" for a specific education app design, which is being expected and seems to be still unfilled, see (Fiala & Koci, 2015). Hence we have already proposed the first version of design principles for these mentally disabled (Fiala & Koci, 2014).

On the other hand, it is obvious, that our first version of proposed design principles cannot be final and calls for further correction and extension. Therefore, we have conducted further usability testing, critical reviews, semi-structured interviews with mentally challenged individuals to find out the most common usability issues, which should be handled in priority. Hence we still continue in this urgent work and extend original design principles by reflecting our latest long term usability testing and identified apps design flaws. Thus, in summary, our original design principles were modified, extended and several new ones were added too (increasing from 10 to 14).

It is expected that some of the proposed principles may already be known or applicable in other situations, conditions or fields that we assume in a HCI context with SEN. Therefore our contribution novelty is not based on each principle novelty and originality, but is expressed by such a set of design principles which leads to recovery from identified usability issues we are facing today in SEN.

2. RESEARCH METHODS AND RESOURCES

In this research we generally put the focus on being involved in this testing process to "*put our hands on and get it dirty*". In order to identify flaws in present apps on touch devices we have firstly established the therapy program (called simply computer therapy) for the mentally disabled as the research ground for prepared usability testing with mentally disabled individuals.

This therapy program was based on the special education cognitive play therapy methodology and was also supervised by Czech experts in special education (Rihova & Jelinkova, 2013). The therapy has also adopted the principles of *i-CT* proposed previously. The therapy (located in a Czech home for the mentally challenged with attached disorders) was provided personally by the corresponding author of this paper for 7 hours per working day during three years, 2012–2014.

2.1. User Group Definition

During this daily therapy we have conducted the series of usability testing (real user-based testing). More than 30 mentally challenged individuals have participated directly and another 10 indirectly by supervision of their key assistants.

With the respect to the whole scope of this three year long-term study, here we just present one of our later testing (conducted in 2014) with consequent flaws identification observed at the conducted usability study (one of the series) in a group of 12 users (age from 20 to 50).

Tested users were mentally challenged (moderate mental disability) with associated combined disorders including physical defects, learning disabilities (LD), Attention Deficit Hyperactivity Disorder (ADHD), Down syndrome and cerebral palsy. They did not have any experience in using a PC, because they were not able to use it due to its complexity (keyboard, mouse, classical OS concept of files and folders). Some of these participants used to visit a class in a special school several years ago, but there was no driven continuity in obtained competences development. All of them had a low vocabulary and some of them had a low ability to speak. Some participants were able to count to 10 (addition and subtraction only), but counting over 10 was unreachable, and some of them were not able to count at all. There was no knowledge of any foreign language at all.

2.2. Hardware and Software Resources

In this case of usability testing users were working with tablet computers. This group of users covered users with different main specific needs, therefore several and different applications (covering user's specific educational needs – SEN) were tested in this study. A tablet computer platform (Apple iOS) was selected with respect to required user's SEN in applications on a selected platform. Finally, the following HW and SW resources were employed:

- *Apple iPad* 4th generation, 10" display, OS: iOS 7.
- *Niki Talk, C.P.A., Kabosil, VOXkom* (apps for alternative and augment-tative communication – AAC).
- *Touch the Sound, Sound Touch 2, Match it up, Little Finder, My little suitcase* (education in vocabulary).
- *Pocket pond, Fluidity, Gaze HD, Plasma globe, Tiny piano, I can xylo, Music sparkle, Guitar free, iAm Guitar, Magic Piano, Doodle Buddy, Draw 4 free, Kids paint, Let's Create!*
- *Pottery HD Lite, 123D Sculpt, 123D Creature* (training, motivation, play therapy apps).
- *BitsBoard, ABC Chiffres, ABCD for children, My first words* (reading and writing apps).
- *Add testic, Sub testic, Free Clock, Czech money, Missy math stage 1* (education in little math).

2.3. Task Scenarios and Usability Testing

The 12 individuals were grouped into smaller groups according to their disability and abilities, development in specific needs which was the object of their therapy. Each group is described by its own case of study and scenario.

2.3.1. Scenario for group in augmentative and alternative communication (1)

The group contained 3 individuals with moderate intellectual disability and some physical movement defects. Touch screen platform was usable in some tasks, thus we have supported these individuals with AAC apps as their main task for alternative communication focused on basic daily phrases.

2.3.2. Scenario for group in vocabulary development (2)

Group consisted of 4 individuals with moderate intellectual disability with further disorders (ADHD, Down syndrome). These individuals were able to speak but had a very limited vocabulary. Therefore, we have focused on vocabulary development through proper apps on touch screen platform as listed in previous section. The participant's task was to learn new words from a given vocabulary setup in available applications.

2.3.3. Scenario for group in reading, writing and math skills (3)

Group consisted of 5 individuals with moderate intellectual disability. All of them used to visit a class in a special school several years ago, but there was no further driven continuity in obtained competences development. Their speech was limited, but they could express whole sentences and they had some ability in reading and writing. They also had some experience in a little math (up to 10 addition and subtraction). Therefore, we operated with apps (as listed in section 2.2) for reading, writing and math development to extend their original skills in this area. The participant's task was reading and writing of known words from given a vocabulary setup in application and little math training.

2.3.4. Usability testing description

Primary goal of this usability testing (testing with real users) was not the identification of the best applications (usability comparison among available apps), but the identification of their flaws observed through a set of available apps for each specific group. At the beginning (preparation phase – 2 hours per week during one month) each participant was introduced to iPad through training, motivation, play therapy apps (see section 2.2) which were used during the daily therapy program.

Afterwards (testing phase – 2 hours per week during 6 month) each participant was asked to perform his specific tasks described in his scenario. Each participant used several applications for his tasks (see section 2.2) and whenever the user was not able to complete his task (partially or totally), the participant was interviewed via a semi-structure interview to describe the reason as much as possible. During this long term testing the participant's reasons were progressively corrected and checked by a therapy assistant (whether stated cause is truly reasonable). At the end of usability testing all unreachable states which should be reached in a user task and which also passed through reasonable progressive correction and checking, were marked as identified flaws. As a final output we have observed the list of identified flaws of application designs which are described in the following section.

3. RESEARCH METHODS AND RESOURCES

3.1. Identified Flaws of Mobile, Touch Platform Applications

In this section we summarise the list of the most common identified flaws observed during conducted long term usability testing and inspection cognitive walkthrough as described in the previous section. In spite of different tasks completion during usability testing performance, we can track common issues which are consequently grouped in a joint flaw categories as follows:
1. **Protection, security lacking** – apps setting is mostly without any access restrictions, setting is not protected and can be improperly changed by users. Moreover, any individual can use the app for unlimited time if not guided properly (this may lead to improper addiction or habits). On the other hand, the app can be switched on or off easily which allows an individual to escape from education/therapy program inappropriately.
2. **Accessibility lacking due to price inaccessibility** – some required applications are not accessible due to their application price, thus disabled individuals cannot use or access these apps as needed.
3. **Internationalization and localization lacking** – missing the option of national (e.g. Czech) user interface, control.
4. **Individual SEN lacking** – missing user accounts, profiles, account protection.
5. **Presence of non-perceptible affordances** – some parts of user interface (affordances) are not perceptible, not as intuitive as needed (i.e. scrolling is difficult to discover, some elements, pictures, lines, buttons were designed too small to be controlled correctly even on 10" tablet computer – phenomenon of fat finger).

Scenario number	End-user	Gender	The occurrences of app design flaws according to their category*							
			1	2	3	4	5	6	7	8
1	Maria	F	x	x	x	x	x		x	x
	John	M	x	x	x	x	x	x	x	x
	Bob	M	x	x	x	x	x		x	x
2	Michal	M	x	x			x	x	x	
	Tom	M	x	x	x	x	x		x	
	Peter	M	x	x			x	x	x	x
	Robin	M	x	x	x		x	x	x	x
	David	M	x	x	x	x	x	x	x	
3	Otto	M	x	x		x	x	x	x	x
	Joseph	M	x	x	x	x	x	x	x	x
	Gabriela	F	x	x	x	x	x	x	x	x
	Helen	F	x	x			x	x	x	x
Flaw frequency in %			100	100	66,7	66,7	100	75	100	75

*Each flaw occurrence was marked according to usability testing method, see section 2.3.4.

6. **App customization lacking** – low or difficult app customization/modifications in app setting (for example in the case of AAC app, it is not possible to change existing pictograms in some categories).
7. **Platform isolation, dependency** – app is available for one platform only (e.g. Apple).
8. **Works online only** – app or its partial functionality is accessible only as a web-app, it could not be fully used outside the range of Wi-Fi connection.

As we can see in Tab. 1, each flaw occurred for more than 50% of all users. Even when one instance occurs such a flaw can be a logical reason to think about the usability improvement for mentally challenged users, but there appeared much more than one incidence only.

3.2. Extending the Computer Therapy Design Principles

Here we present the extension of the previous simple 10 principles to 14 design principles according to the latest testing and flaws identifications. Each principle is described by its problem description and its prescription – the proposed solution. First, previously published positive results (Fiala & Koci, 2014) led us to this revision and extension of the first version of design principles.

For comparison, the first basic 10 design principles were extended by principles marked as no. II, XII, XIII and XIV in this paper.

Furthermore each of the original design principles was also revised by defining descriptive and prescriptive parts and thus making clear and simple redefinition with use case examples corresponding with UML representation

(each design principle is possible to express at least by one domain model e.g. in the UML with OCL representation, see section 3.3). The reference to a specific identified flaw is marked in brackets (expresses which principle handles one of the specific identified flaws, as listed in section 3.1).

I. The principle of platform independence (multiplatform). [7]
Problem: mentally challenged individuals cannot care about variety of platform producers, or why this is not working on my device, or why this is not compatible. They simply need their app working on their device.
Solution: designed and developed app (i.e. application for AAC) should be supported on multiple platforms (i.e. mobile touch platforms with operating systems like iOS, Android or Windows), to launch with a similar look and feel behaviour as much as possible.

II. The principle of "*online*" independence. [8]
Problem: life-style of mentally disabled is in contrast with world-wide trend of cloud solutions and "*Internet of Things*". Mentally challenged individual needs a robust, stable app everywhere and anytime. They cannot handle or care about the reasons of non-working web service/app or whether my location has some available connection with optimum throughput.
Solution: SW – applications should be developed as native or hybrid rather than web applications to support accessibility and usability independent on an internet connection, which cannot be properly accessible in every life-style situation of the mentally disabled as needed.

III. The principle of multidisciplinary attitude.
Problem: mentally disabled individual is usually very dependent (during the whole life) on services of social care, health care and continuous education which is in contrast with a common, intellectually capable individual.
Solution: the design and development of app should meet the requirements concluded from specific educational needs (SEN), demands from social, health care, all confronted with ICT constraints. The whole application should reflect the real objects situations from these four areas at least.

IV. The principle of free, open accessibility (OA). [2]
Problem: in general, working life of a mentally disabled person is not financially fruitful enough to cover all their expenses and, therefore, if the required app is not accessible due to its cost, then unfortunately there is no accessibility and usability too.
Solution: final app should be distributed as freeware or available at low accessible cost, SW should prefer availability under open public licence (including codes for further open development by community of experts).

V. The principle of proper SW techniques.
Problem: it is uneasy (even in cases of multidisciplinary attitude) to map properly the complexity of the world of mentally disabled reflecting all their needs and limitations. Thus we can always create only the representation at a certain level of inaccuracy.
Solution: SW design and development techniques should use such methods to map the "*real world of mentally disabled*" as precise as possible and needed. SW techniques of real world object mapping like OOP should be included with related modern IT standards. This includes the proper choice of SW architecture, for example, MVC architecture, see (Veit & Herrmann, 2003).

VI. The principle of SEN purpose priority. [4]
Problem: there are many needs in the life of the mentally challenged, but for purposes of special education and therapy (in terms of special pedagogy) there are key needs – SEN, as also noted in "*The principle of multi-disciplinary attitude*".
Solution: to guarantee the app's purpose for education and therapy, SEN should be primarily reflected and implemented as the main app's purpose. Consequently the final app should be accessible and usable primarily in the scope of this SEN purpose (i.e. categories and its word/pictogram cards in an application for AAC).

VII. The principle of "*beyond the school walls*".
Problem: the education and therapies of mentally challenged are not restricted by school walls only in their common daily practise but are continuing in collaboration and interconnection with other provided services (e.g. parts of social, health services).
Solution: app should be designed, developed as usable in the school environment (i.e. integrated in common school, or in special education) and out of school education, free time activities, games, see (Fiala & Koci, 2014), common daily life environment, including the sector of social-health services, in summary usable in conditions where disabled individual lives or moves.

VIII. The principle of individual content (educational/therapy). [4]
Problem: besides the need for a multidisciplinary attitude (described in "*The principle of multidisciplinary attitude*") there is the need for an individual educational/therapy attitude which reflects specific/individual educational needs (individual content) of each mentally challenged individual.
Solution: app should offer the customisation for individual education/therapy content (e.g. customisable set of pictograms/categories in the case of AAC application). Individual content should also reflect individual plans (i.e. respecting individual limitation, health condition, activities, and hobbies).

This customisation should be protected from unwanted changes caused by accidental touches and this protection is further handled by "*The principle of safety and protection*" below.

IX. The principle of continuity.
Problem: the instant, continuous education/therapy program is important in the life of the mentally challenged individual (in case of over school individuals we talk about free time pedagogy and therapy programs which can be offered continuously). Only this way the learned, obtained competences can sustain and possibly increase too.
Solution: a designed and developed application should be prepared for long term and everyday intensive usage. This includes the support for a variety of educational content for each individual and offering future app support (e.g. available in a form of unknown issues, bugs reporting or user's suggestions reporting for further app development).

X. The principle of usability and affordances amplification. [5]
Problem: generally each control or other action element in user interface should suggest its usage (affordances). In the case of mentally challenged individuals, this rule should be multiplied (amplified) by the degree of intelligence deficiency or deficiency in perception abilities. A similar situation occurs in the focus on user interface element's practical usability. A user interface element may be usable (touchable) for an intellectually capable individual, but not usable (touchable) for a mentally challenged individual with worse perception or deficiency in soft motoric functions.
Solution: each element of user interface should be formed well enough (size, shape, colour, sound response) to suggest its usage, even for the mentally disabled e.g. using simplified and amplified principles of "*Design of everyday things*", see (Norman, 2013). Size of elements should be large enough to avoid "*thick finger effect*" and distances among elements should allow freer place to avoid of multiple action-button touches. Furthermore, all gestures should be intuitive, simply based on common-known, real world gestures (real world of mentally challenged).

XI. The principle of assistive mode. [1]
Problem: in special education/therapies many of the given tasks are dependent on the assistance of a special tutor or a social/health care worker. The need for assistance may still be necessary even in cases of tasks realised on a touch device (e.g. tablet computer). Besides the assistive mode required in real time task completion, the assistive mode is also required for a proper app, educational content customisation, setting before the education/therapy is started.

Solution: besides an end-user account, each app should offer other types of accounts. The first is an assistive account for setting and modification (i.e. personalisation of education content: adding or removing functions, time lock or screen lock) according to individual needs (i.e. for teachers, instructors, assistance). It should be possible to simply switch between these accounts, even during real time task completion work with the mentally disabled.

XII. The principle of administration mode. [1]

Problem: in common special education/therapy one educational tool (including tablet computer with specific educational app.) is used by many special tutors for several mentally challenged users. Meanwhile, some demands of special tutors and some SEN of their users may be very similar, while some of them may differ. This leads to demand of further administration.

Solution: besides the assistive mode – account described in the previous principle of assistive mode there is a need of administration mode (account) to guarantee the control over multiple special tutor's accounts. The administrator can operate over app permissions (restrictions, see below), even over the special tutor's accounts. Moreover, the administrator should be able to make a copy of accounts (assistance, special tutor, and end-user) and pass its setting, customisation to new created profile or replace some of the existing profiles.

XIII. The principle of internationalization and localization. [3]

Problem: for the most ofmoderate intellectually challenged users it is almost impossible to understand and use other foreign languages.

Solution: to guarantee the usability and accessibility for intellectually challenged users, the app should fully support individual internationalization and localization.

XIV. The principle of safety and protection. [1]

Problem: improper usage of electronic data (e.g. games) may lead to addiction even in cases of an intellectually capable individual. Furthermore, some data available in apps or available through such apps or internet browsing may include or lead to "*inappropriate explicit content*". Moreover, in spite of the application of "*the principle of online independence*" (app online independence) the tablet computer can still be connected to the internet or there might be some inappropriate apps installed on the device. Therefore, the question of safety and protection still remains uncovered. In contrast, intellectually disabled users are not able to recognise the risks of such apps, content and thus should be protected as much as possible.

Solution: an app should offer safety usage in terms of the prevention and protection from abusive or addictive practices which an intellectually disabled individual cannot recognise or prevent. This includes the prevention from inappropriate explicit content e.g. violence, hate or addictive practices like internet pornography, see (Kleponis, 2012). The application should allow time and content restrictions (blocking the escape from an app, e.g. "*kiosk mode*"), which are customisable in administration mode.

Although some of the proposed principles may appear as standalone, in this proposal all 14 design principles create one aggregate and are interconnected, one principle assumes the presence of others. Hence all principles are assumed to be applied in each app development for mentally challenged users (special education and therapies). If a principle application cannot be handled (e.g. due to technical issues), we assume its maximal application (apply the principle as far as possible) to support at least part of the principle.

3.3. *i-CT* design principles as domain models in MDE for apps development

In software engineering common practices (developmental methodologies) we transit through developmental cycles where formal software modelling is usually required. This formal representation is usually expressed by diagrams in UML. One of common developmental methodologies is the model driven engineering (MDE) and domain driven design (DDD), see (Evans, 2004) and (Schmidt, 2006). In these developmental methodologies we operate a with domain model representations which are used for further code generation in the implementation phase. By application of MDE and DDD methodologies, *i-CT* design principles represented in UML domain models also serve as the enhancement of software developmental process (apps for mentally challenged). Hence proposed design principles are not only represented as abstract plain text claims, but they are also expressed by an UML with OCL extension and thus create domain models which are directly applicable in further software developmental process.

In detail, obtained domain models are used for code generation of a common framework which is consequently used for each specific app development (development driven by framework). Thus, by utilization of domain models in UML the SW developmental process of certain apps are enhanced by automation of this process. In result, a specific demanded app for the mentally challenged is developed and deployed faster. Thus, the practical accessibility is also increased in terms of HCI.

The first version *i-CT* design principles have already been expressed in UML, OCL domain model representations which were used for the first framework generation and this framework was consequently utilised for development of the first 3 apps for mentally challenged, (see the next section for detail).

The same process is now expected with an updated, revised new version *i-CT* design principles which are presented in this paper. But this process completion in now in progress, (see chapter 4 "*On-going and future work*"). For demonstration purposes here we can present two of the proposed designed principles in formal UML representation, specifically in a class diagram. Following figure 1 describes a domain model in UML class diagram representing the principle of assistive and principle of administrative modes (no. XI and XII).
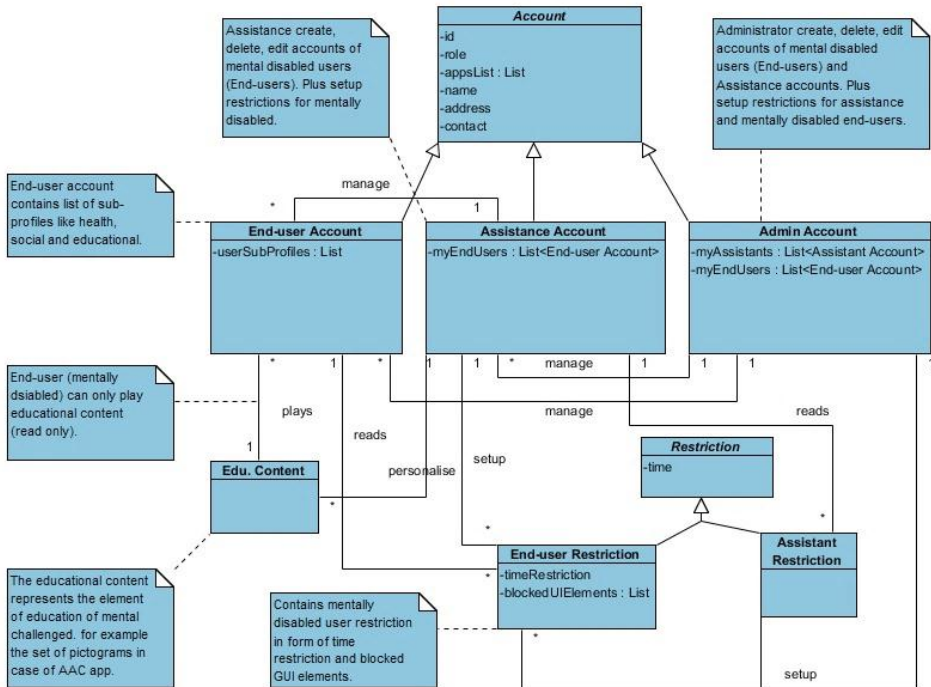

Fig. 1. The draft of possible realization of the principle of assistive and administrative mode in the UML domain class diagram (own study).

As we can see the design principle no. XI and XII sets specific constraints, conditions in object oriented design, and thus generate the stub of the domain model. In the case of class diagrams this leads to a generation of specific classes, associations among end-user account, assistance account, administration account, educational content (education content) and restrictions, where associations among classes have specific constraints and properties.

Moreover, each core class prescribes the list of methods (operations) which should be handled in the implementation process. Even in this simple example, it is obvious that by respecting these examples of design principles of assistive and administration mode represented in UML, we eliminate an inappropriate

design which may lead to one of identified flaws in the result and thus to a significant reduction in end-user usability and accessibility (as justified in principles description). On the other hand it is obvious that for each of proposed design principle there exists one or more proper domain model representations. Hence we assume at least one of proper model representation which is released collectively with the implementation of our proposed revised design principles in*i-CT*framework and its superstructure apps (see section 4 "*On-going and future work*").

3.4. Demo Example: Mentally Challenged as Models for Their Applications

As we have noted in the introduction, this research is significantly interconnected with practical work and implementation. Since 2013 we have started the development of first open source framework (called *i-CT framework*) which implements models of the first 10 design principles in UML to a practical framework. In 2014 the first version of *i-CT* framework (version 1.1.0) was released, see (Fiala, Koci & Vejtasa, 2014).

Presently we are extending our original first framework by the application of the revised, proposed 14 design *i-CT* principles at present and consequently, we are also preparing the design of new apps (see section 4 "*On-going and future work*" below). We cannot demonstrate the whole positive impact of these extended, revised design *i-CT* principles here. Therefore, to provide some demonstration of the positive impact of these *i-CT* principles to usability issues, we recall previously released applications. These apps were built based on first framework version generated from domain models obtained from the first 10 design principles according to MDE and DDD methodologies. A list of these first apps is below:

- *EasyTalk*: application for alternative, augmentative communication (AAC).
- *SignToLanguage*: application for training and testing of sign to language.
- *YesNoCommunication*: application for elementary AAC.

Each of the developed applications was verified previously during usability testing in comparison present similar applications at present. Each of them had provided higher usability and accessibility in comparison with the corresponding apps. Here we recall a closer one of the developed app, called *EasyTalk* (the AAC application). This app simply demonstrates the way the accessibility and usability is also increased if *i-CT* design principles (even the first proposed version) are properly adopted and respected in software engineering process.

The common goal of any proper AAC app is to compensate and reduce the speech disability (Beukelman & Mirenda, 2005). In case of mentally challenged inividual with speech disability, AAC often represents the only way to communicate. Hence the usability and accessibility of such AAC application is critically important.

In recent years the usage of AAC apps on tablet computers have proven significant results when working with the intellectually disabled, see (Bradshaw, 2013; Fiala & Koci, 2015).
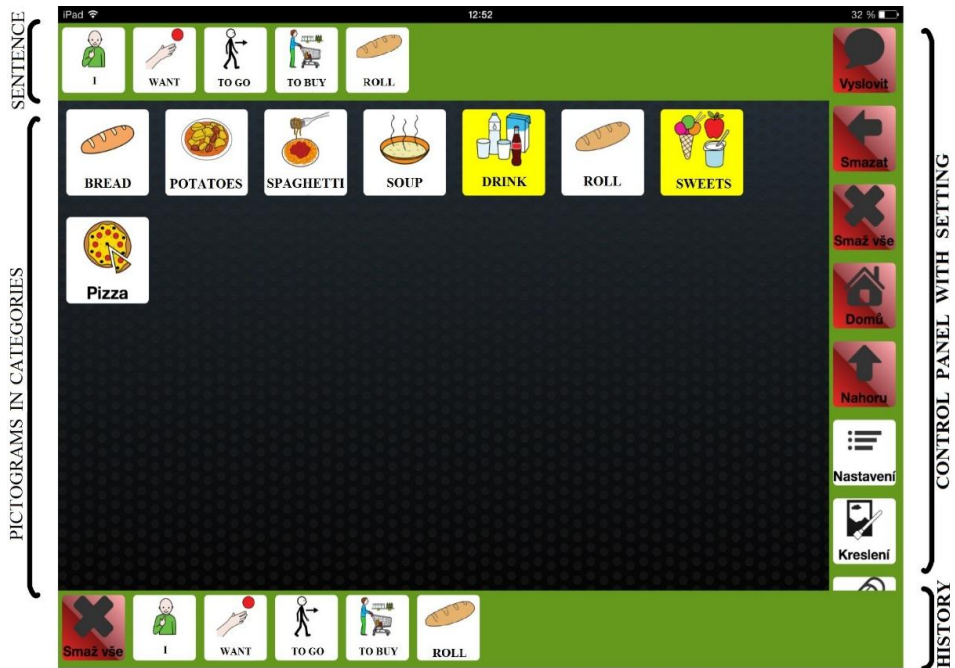

Fig. 2. *Easy-Talk* **application desktop is accessible in several languages including Czech – in comparison with other AAC apps, this desktop is also customizable by different visual styles andits control panel contains more functionality for AAC expression (own study)**

Tab. 2. AAC application *EasyTalk* in HCI factors comparison with other present applications (own study)

AAC apps	Important AAC application functionality related to HCI factors*								
	Assist. support (**XI**)**	User accounts (**VIII**)**	Multi-platform (**I**)**	Editable content (**VIII**)**	Sentence history (**VI**)**	Canvas (**VI**)**	Text input (**VI**)**	Free distr. (**IV**)**	Open source (**IV**)**
Easy-Talk	YES	YES	YES	YES	YES	YES	YES	YES	YES
Klabosil	NO	NO	NO	YES	YES	NO	NO	YES	NO
Niki Talk	NO	NO	YES	YES	NO	YES	YES	NO	NO
C.P.A.	YES	YES	YES	YES	NO	NO	NO	YES	NO
Grid Player	NO	NO	NO	YES	NO	NO	NO	NO	NO

* HCI factors were based on comparison of two designs, one with supported functionality available in *EasyTalk* app and partial or missing functionality available in other AAC app.
** Roman numbers in brackets denote design principles which were used to improve the functionality in *EasyTalk*.

Unfortunately many of these apps include HCI factors (e.g. as noted in Table 2) which lead to inappropriate usability issues, see (Fiala & Koci, 2015; Vejtasa, 2014). Therefore, we have previously implemented the above mentioned *EasyTalk* app to handle some of these issues and also through a proper software development strategy based on the described utilisation of *i-CT* design principles. For *EasyTalk* app illustration see Figure 2.

The first positive outcomes demonstrating the comparison of *EasyTalk* app with present similar AAC apps were already published in (Fiala & Koci, 2015; Vejtasa, 2014).Table 2 recalls an observed comparison of *EasyTalk* app with other present AAC apps used for special education and therapy (the key of comparison are HCI factors).From the recalled observed data and *EasyTalk* app usability testing we can see that implementation of *EasyTalk* app according to proper software development strategy based on noted utilization of *i-CT* design principles had finally led to an improvement of usability in comparison with other similar present AAC apps.

If we consider the first *i-CT* design principles and proposed extension and revision of *i-CT* design principles as presented in this paper, it is clear to claim that based on the provided justification the analogous utilisation of presented 14 extended *i-CT* design principles into SW development process will also lead to an improvement of usability and accessibility in specific apps (at least in the cases of previously developed specific apps). On the other hand, the full evidence can be done only through implementation and testing of specific apps and its consequent comparison with similar apps, which is now in progress.

4. ON-GOING AND FUTURE WORK

As noted in section 3.4, based on the first version of the design principles, the framework and several applications for special education/therapy of mentally disabled were already developed.

By revision and extension of these design principles as proposed in this paper, the previously developed framework should be revised and extended, too. The same holds for the previously developed apps based on this framework. This is the task of the present on-going work. At present, we are extending previously developed apps and new apps (e.g. app for real time sign language translation and other apps for communication) were also added. For all developed apps and framework hold the same as previously, all software is licensed as freeware under public domain (open source) to underline the accessibility factor.

The domain model (mostly based on UML with OCL) package, including the possible model representations as domain diagrams of each principle, is going to be included within the new framework release. Once the framework and apps will be finalised, we are going to conduct further usability testing to observe the full evidence of usability improvement of developed apps in comparison with present and similar comparable apps.

5. CONCLUSION

The usability and accessibility of ICT resources are key factors for each mentally challenged individual. This importance was further increased by the new possibilities of touch devices (tablet computers, smartphones) which were observed in special education and therapies (Hayhoe, 2012; Isasi, Basterretxea & Zorrilla, 2013; Jowett, Moore & Anderson, 2012). In spite of many positive HCI factors of the touch devices for mentally disabled, there still remain usability and accessibility issues which should be discussed and handled (Fiala & Koci, 2014; Nielsen & Budiu, 2013). Hence, since 2012 we have started a daily "*tablet computer*" special therapy program for the mentally challenged (simply called "*computer therapy*" program) to identify the main usability issues and to consequently verify the proposed solution. Based on the first identified usability flaws we have proposed the first version of *i-CT* design principles which were further expressed as domain models and used in MDE for the generation of the practical framework which was consequently applied to development of practical apps for special education. During the long term usability testing, these first apps have provided the evidence of improvement in usability and accessibility. Thus we have enhanced the SW development process itself and have overcome insufficient functionality referring to specific HCI factors see (Fiala & Koci, 2014, 2015; Vejtasa, 2014). This improvement was achieved due to a proper developmental strategy obtained through the proposed *i-CT* design principles applied into a software development process by the usage of MDE and DDD methodologies. In this paper we also presented one of our final usability testing which has led to the identification of further usability issues. Based on this identification and evidence we have revised the first version of *i-CT* design principles by:

- Redefinition of each principle (in the form of clear problem description and prescription to provide clear and specific requirements usable simply in SW life cycle e.g. MDE).
- Extension of these principles by 4 new principles (reflecting noted flaws).
- Expressing principles in UML with OCL representation (to inject the proposed principles into the design model directly).

The goal of this paper was to present important usability issues (identified flaws) observed during our testing and propose the proper design principles to handle such issues and furthermore, to demonstrate its positive improvement in usability and accessibility in apps for mentally disabled. The demonstration of the positive contribution was provided based on justification and a comparison with a previously proposed first version of *i-CT* design principles which have proven the improvement in usability and accessibility in specific apps. As noted in section 1.2 and 2, our practical oriented research goals led us

to noted specific criteria on design principles. Although this criteria seems to be strictly specific, it addresses the field of special education, therapy which awaits for solutions of practical usability issues. Hence here we continue in this effort and present further results of conducted usability testing (identified flaws) and propose the revision and extension of the previous first version of design principles for the mentally disabled. As we have started and continued this research in close connection to mentally challenged, it is clear to summarize this contribution by the title "*Mentally challenged as design principles and models for their applications*".

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REFERENCES

Beukelman, D., & Mirenda, P. (2005). *Augmentative and alternative communication*. Baltimore: Brookes Publishing.

Bradshaw, J. (2013). The use of augmentative and alternative communication apps for the iPad, iPod and iPhone: an overview of recent developments. *Tizard Learning Disability Review, 18*(1), 31-37.

Budiu, R., & Nielsen, J. (2011). *Usability of iPad apps and websites*. Fremont: Nielsen Norman Group.

Buhler, C., & Pelka, B. (2014). Empowerment by Digital Media of People with Disabilities. In *Computers Helping People with Special Needs* (pp. 17-24). Springer.

Burgstahler, S. (2008). *Universal design in education: Principles and applications.* University of Washington.

Dobosz, K., Dobosz, M., Fiolka, T., Wojaczek, M., & Depta, T. (2014). Tablets in the Rehabilitation of Memory Impairment. In *Computers Helping People with Special Needs* (pp. 399-402). Springer.

Evans, E. (2004). *Domain-driven design: tackling complexity in the heart of software.* Addison-Wesley Professional.

Fiala (Krajicek), J., & Koci, R. (2014). Computer therapy as concept of new form of therapy for intellectual disabled people: theory and practise. *Journal of Technology & Information Education, 6*(1). 89-103. doi:10.5507/jtie.2014.007

Fiala (Krajicek), J., & Koci, R. (2015). Computer as Therapy in role of alternative and augmentative communication. In *Proceedings of 4th International Conference on Advanced in Computing and Emerging E-Learning Technology* (*18*, pp. 34-42), Singapore.

Fiala, J., Koci, R., & Vejtasa, O. (2014). i-CT Framework version 1.1.0. BUT FIT. Retrieved from http://www.fit.vutbr.cz/~ifiala/prods.php?id=405&notitle=1

Hager, E. B. (2010). iPad opens world to a disabled boy. *New York Times.* Retrieved from http://www.nytimes.com/2010/10/31/nyregion/31owen.html

Hayhoe, S. (2012). Using an iPad as an assistive device to improve technical literacy: Trial usage with an Emirati student. In S. Dowling (Ed.) *Elearning in Action: Opening Up Learning. Educational Technology Series*. Abu-Dhabi: HCT Press.

Isasi, A. R., Basterretxea, A. L., & Zorrilla, A. M. (2013). Helping children with Intellectual Disability to understand healthy eating habits with an IPad based serious game. In *Computer Games: AI, Animation, Mobile, Interactive Multimedia, Educational & Serious Games (CGAMES), 2013 18th International Conference on* (pp. 169-173). Doi: 10.1109/CGames.2013.6632628

Jacobson, I., Booch, G., & Rumbaugh, J. (1999). *The unified software development process (Vol. 1)*. Addison-wesley Reading.

Jowett, E., Moore, D., & Anderson, A. (2012). Using an iPad-based video modelling package to teach numeracy skills to a child with an autism spectrum disorder. *Developmental neurorehabilitation, 15*(4), 304-312. doi:10.3109/17518423.2012.682168

Karwowski, W., Soares, M. M., & Stanton, N. A. (2011). *Human Factors and Ergonomics in Consumer Product Design: Uses and Applications.* CRC Press.

Kleponis, P. C. (2012). The Pornography Epidemic: A Catholic approach. Oldsmar, FL: Simon Peter Press.

Larman, C. (2005). *Applying UML and patterns: an introduction to object-oriented analysis and design and iterative development.* Pearson Education India.

Marinescu, R., & Lanza, M. (2006). *Object-oriented metrics in practice. Using Software Metrics to Characterize, Evaluate, and Improve the Design of Object-Oriented Systems*. Springer.

Martin, R. C. (2000). Design principles and design patterns. *Object Mentor, 1*, 34.

Nielsen, J. (1994). Usability engineering. Elsevier.

Nielsen, J., & Budiu, R. (2013). Mobile Usability. MITP-Verlags GmbH & Co. KG.

Norman, D. A. (2013). *The design of everyday things: Revised and expanded edition.* Basic books.

Pearson, J., Buchanan, G., & Thimbleby, H. (2010). HCI design principles for ereaders. In *Proceedings of the third workshop on Research advances in large digital book repositories and complementary media* (pp. 15-24). ACM.

Rihova, L. (2013, March). The possibilities of iPad application in special education. *INSPO: 10th conference on Internet and Information systems for people with specific needs.*

Rihova, L., & Jelinkova, I. (2013). Introducing iSEN initiative. *Apple Accessibility Summit, 2013, Prague.*

Shah, N. (2011). Special Education Pupils Find Learning Tool in iPad Applications. *Education week, 30*(22), 1-16.

Schmidt, D. C. (2006). Model-driven engineering. *COMPUTER-IEEE COMPUTER SOCIETY, 39*(2), 25.

Signore, A., Balasi, P., & Yuan, T. (2014). You Talk!--YOU vs AUTISM. In *Computers Helping People with Special Needs* (pp. 506-512). Springer.

Stephanidis, C. (2009). *Universal Access in Human-Computer Interaction. Addressing Diversity. 5th International Conference, UAHCI 2009, Held as Part of HCI International 2009, San Diego, CA, USA, July 19-24, 2009. Proceedings, Part I.* Springer.

Vanderheiden, G. C., & Jordan, J. B. (2006). Design for people with functional limitations. In G. Salvendy (Eds.), *Handbook of Human Factors and Ergonomics, Fourth Edition* (pp. 1407-1441). Hoboken, USA: John Wiley & Sons. doi: 10.1002/9781118131350.ch51

Veit, M., & Herrmann, S. (2003). Model-view-controller and object teams: A perfect match of paradigms. *Proceedings of the 2nd international conference on Aspect-oriented software development* (pp. 140-149). doi: 10.1145/643603.643618

Vejtasa, O. (2014). Application for alternative communication for people with mental handicap. *Proceedings of the 20th Conference STUDENT EEICT 2014* (pp. 1-5).

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ARTIFICIAL NEURAL NETWORK MODELLING OF CUTTING FORCE COMPONENTS DURING AZ91HP ALLOY MILLING

Abstract

The paper presents simulation of the cutting force components for machining of magnesium alloy AZ91HP. The simulation employs the Black Box model. The closest match to (input and output) data obtained from the machining process was determined. The simulation was performed with the use of the Statistica programme with the application of neural networks: RBF (Radial Basis Function) and MLP (Multi-Layered Perceptron).

1. INTRODUCTION

Manufacturing advanced machine and equipment elements is inextricably related to the application of new generation structural materials. Application of magnesium alloys enables reduction of weight of manufactured elements and can facilitate decreasing manufacturing and maintenance costs (Pekguleryuz et al., 2013).

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Production of different components involves effective removal of machining allowances, often through the process of milling. "Functional" machinability parameters include, inter alia, forces occurring during machining. The forces in question can contribute to deformation of a workpiece during machining. The increase of these forces can lead to the reduction of undeformed chip thickness. When the latter decreases, the cutting force increases. The rise in the shear energy per unit of volume translates to rising volume of subtracted metal and of the cutting force (Fang et al., 2005). Adhesion and build-up can also have a considerable impact on fluctuation of the cutting force components as well as result in the reduction of the surface quality and shape and dimensional accuracy (Oczoś, 2000). The demand for force in machining various materials, including magnesium alloys, is the subject of numerous studies. Compared to other materials, magnesium alloy treatment can be performed quickly and effectively, which enables machining at a large depth of cut and considerable feed (Zagórski & Kuczmaszewski, 2013; Fu et al., 2015).

Cutting speed is what directly affects the effectiveness of the milling processes. The division that is frequently adopted includes machining performed at conventional parameters and increased cutting parameters, which is the area of various HSM methods. It is possible to define the "transition" point into HSM parameters as $\partial F/\partial v_c < 0$ for HSM and $\partial F/\partial v_c > 0$ in the case of conventional machining. It is broadly accepted that what distinguishes HSM from conventional machining is that in HSM the increase in the cutting speed v_{cb} results in the decrease in the cutting forces. On the other hand, HSM machining is often defined as a high-performance cutting method which facilitates obtaining high quality of machined surface. The use of HSM helps to eliminate finishing operations which have been traditionally realised through grinding (Adamski, 2010).

In AZ91HP alloy milling with PCD cutter and in the presence of cutting fluid cutting forces assume low values and grow linearly with the increase of feed. Lower cutting forces can translate into smaller tendency for tools to overheat (smaller coefficient of friction at a tool-workpiece interface). What can be observed along with lower cutting forces, especially as far as small cross-section of a machined layer is concerned, is a significantly lower temperature in the cutting area (Oczoś, 2000, 2009).

In feed per tooth f_z (in machining with Kordell geometry tools), the Fx and Fy components and their amplitudes rise with the increase of feed. In the case of cutting with cutters of traditional tool geometry, a more significant influence on cutting forces and their amplitudes is observed when changing the feed per tooth f_z rather than cutting speed v_c; the highest values of the cutting force components were obtained for the PCD cutting edge tool and AZ91HP alloy. Furthermore, it ought to be remarked that the cutting force components decrease with the increase of cutting speed to v_c=1200m/min in traditional tool geometry (Zagórski & Kuczmaszewski, 2013). Another relevant factor is tool geometry

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and its impact on the cutting force components and their amplitudes. Research studies in the field generally focus on the changes of specific technological milling parameters (v_c, f_z, a_p) with the application of carbide cutters of variable tooth geometry ($\gamma=5°$ and $\gamma=30°$). Lower values of cutting force components and their amplitudes indicating a greater stability of the process were observed for the tool $\gamma=30°$. Increasing the depth of cut triggers a proportional increase in the cutting force components and their amplitudes. A change in the feed per tooth (in the range of $f_z=0.05\div0.15$mm/tooth) provoked the rise of the cutting force components and subsequently their stabilisation (for $f_z=0.15\div0.3$mm/tooth) (Gziut et al., 2014). Another factor of high importance is the impact of cutting tool coating (such as the TiB_2 and TiAlCN type) on cutting forces in milling with carbide tools. The lowest values of cutting force components (F_x, F_y) in milling Al6082 alloy were obtained for a tool with a TiB_2 coating. During the v_c change, the characteristic point of „transition" to the range of HSC (where $v_{cgr}=450\div600$m/min) was observed (Kuczmaszewski & Pieśko, 2013). In addition, cutting force component amplitudes, which are a significant indicator of the cutting process dynamics, assume the highest values for indexable tools (which should be taken into account when selecting a tool for a particular application) (Kuczmaszewski & Pieśko, 2014).

Furthermore, excessive cutting force value can have a negative influence on the quality of machined surface. Increasing feed results in higher vibrations generated in the milling machine-milling cutter-workpiece-fixture system, which is triggered by excessive cutting force (Kim & Lee, 2010). Nowadays machining processes are increasingly frequently modelled with both mathematical modelling methods (Danis et al., 2016) and advanced artificial intelligence systems (Cus et al., 2007).

Despite multiple advantages, subtractive manufacturing of magnesium alloys involves multiple risks. Magnesium dust emerging during machining has a negative impact on both the staff operating machine tools and the machine tool itself. Moreover, magnesium is susceptible to ignition, which can occur as a result of a rapid temperature increase. Another problematic matter can be formation of build-up at the tool edge or rake face, which results from intensification of adhesion (Oczoś 2000, 2009). Thus, the analysis of the actual cutting force values and computer simulation can have a beneficial influence on the stability and effectiveness of Mg alloy machining and safety prediction. Anticipating cutting force component values seems considerably significant from the viewpoint of magnesium alloy machining due to deformations of thin-walled elements. The model enables selecting the technological parameters in a way that it is possible to obtain required force component values without producing machining errors.

2. RESEARCH SUBJECT

The simulation of cutting force components was performed for the AZ91HP magnesium alloy milling. For that purpose, experimental analysis was carried out. The applied tool was a double-bit carbide fly cutter with TiAlN coating and with a plain parallel shank, belonging to the group of cutters intended for machining Al and Mg alloys. The dimensions of the milling cutter were the following 16x25x100 mm W-Z2, $\lambda s=30°$. The scope of the technological parameters comprised v_c=400-1200 m/min, f_z=0.05-0.3 mm/tooth. Parameters such as milling depth a_p=6 mm and milling width a_e=14 mm were constant in the conducted tests. Machining was performed on a vertical machining centre Avia VMC800HS with the control system Heidenhain iTNC 530 offering maximum spindle rotation speed of n=24000 rpm and minimum feed of 40 m/min. In order to measure the cutting forces, piezoelectric dynamometer Kistler 9257B was applied together with the amplifier 5017B. The dynamometer allowed measuring the forces within the range of –5 kN to +5kN. The sampling rate was 5kHz.

In milling, particularly at increased cutting speeds, the importance of dynamic cutting force components rises. What should be done in order to determine their value is their identification. The difficulty that arises here is the fact that the model of the phenomena emerging in the cutting area during milling is highly complex and non-linear. The outcome of force interactions is the mutual dislocation of the object and the tool in their area of cut. Non-stationarity poses yet another obstacle which results from the character of cutter feed movement. The measurement of the cutting force is impeded as it requires a dynamometer to be installed in the machine tool. Furthermore, installing any dynamometer impacts the dynamic properties of the milling machine-milling cutter-workpiece-fixture system. The adoption of such a solution is currently difficult in industrial conditions. There is, however, a remarkable correlation between the technological machining parameters such as feed, cutting speed, depth and width of cut.

Consequently, a question whether it is possible to predict the cutting force – its components should be asked. The answer to this question can be obtained by approaching the milling process as a control object. Therefore, the analysis of such an object should be carried out. Also, controllable inputs and outputs of a model occurring as a result of the identification should be determined. This can be obtained through the application of the Black Box model, *i.e.* specifying the closest match between certain (input and output) data produced by the system. This kind of a solution can be applied when it is difficult to define a mathematical equation describing the process due to its complex character (Awrejcewicz, 2007; Kuc, 2014).
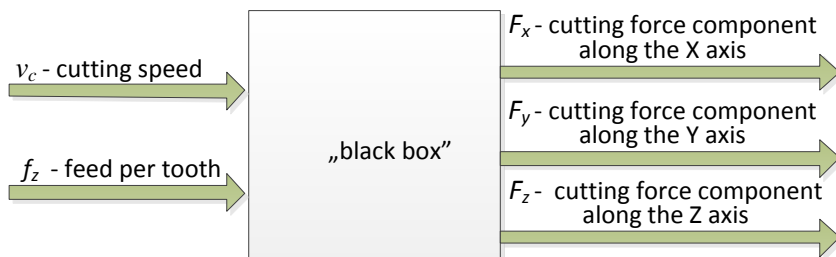
Fig. 1. The model of the milling process (own study)

Controllable parameters that a technologist has at his disposal are cutting speed v_c, feed per tooth f_z, cutting depth a_p, cutting width a_e, tool geometry (including the rake face or the inclination angle of a helix). When machining process is considered as a control object, output rates are the following cutting force components: F_x – cutting force component along the X axis (also described as feed component F_f), F_y – cutting force component along the Y axis (the normal component to the feed force F_{fn}) and F_z – cutting force component along the Z axis (reactive component F_p). In tests, cutting speed v_c and feed per tooth f_z were variable input parameters, the remaining ones were constant. The model of the process is presented in Fig. 1. Assuming that the process of machining of a specific part is repeatable, force input and cutting conditions in selected points of the tool path can be similarly considered repeatable. Several requirements should also be set regarding the accuracy of this assumption, i.e. cutting should be performed with a sharp tool and at constant cutting parameters for consecutive machining cycles.

3. NEURAL NETWORK MODELLING

The aim of the modelling is to predict the course of non-linear technological processes with the application of trained neural networks. Its analysis can contribute to the creation of a system which could support decision-making processes in an enterprise (for instance through optimization of milling process focusing on the selection of suitable technological parameters of machining).

For the purpose of cutting force components simulation, artificial neural network was used. The applied software was Statistica. During testing, two networks scrutinised: RBF (Radial Basis Function) and MLP (Multi-Layered Perceptron). Each component of the cutting force was modelled separately. Their values were calculated as the average of the maximum values from the 10 ranges separated from the stable machining area. It constituted the output value for individual models.

The networks were built with one hidden layer. The input layer consisted of two neurons whereas the output layer – one. Both the number of the training epochs (100) and the number of neurons in the hidden layer (1÷10) were selected experimentally. In order to create a simulation of all three cutting force components, 3 models of artificial neural networks were built. The input modelling parameters were cutting speed v_c and feed per tooth f_z. The outline of such a network for the cutting force component F_x is presented in Fig. 2. The outlines of the remaining components were analogical, relevant cutting force components were obtained as model outputs.
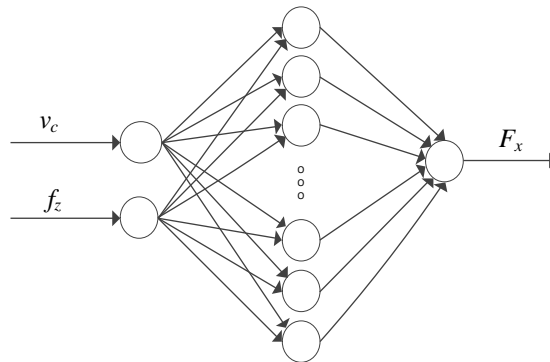

Fig. 2. Artificial neural network outline of the cutting force component along the X axis – F_x (own study)

The training of the MLP network was performed with the use of the BFGS (Broyden-Fletcher-Goldfarb-Shanno) method. It produced the best results in the reduction of functions to the required level at the shortest possible time. During the simulation, the following application functions were applied: linear, exponential, logistic and tanh. RBF network was trained with the RBFT method. The activation function for hidden neurons was Gaussian distribution, for input neurons – linear function.

The modelling was conducted focusing on 17 sets of machining parameters, 14 of which were used for training. The training group comprised 80% of the measurement results, 20% was validational. The remaining parameter sets were applied for the verification of the simulation accuracy. Due to the small amount of data sets, the test group was not created (Szaleniec, 2008).

From among obtained cutting force components simulations, on the basis of the smallest training error and the highest quality of training, the most effective MLP network models were selected. Afterwards, they were compared to the simulation based on the RBF network. The training error was determined by the method of least squares.

The parameters of the best MLP and RBF networks for specific cutting force components F_x, F_y and F_z are presented in Table 1. On the basis of the analysis of the obtained network models, it can be stated that in the case of all cutting force components the best results were achieved for the MLP networks (F_x – MLP 2-4-1 having four neurons, F_y – MLP 2-9-1 having nine neurons, F_z – MLP 2-8-1 having eight neurons). For the modelled components, the quality of the MLP and RBF networks was comparable, however for the MLP network much smaller training errors were obtained. It is therefore suggested that the recommended network should be MLP.

Tab.1. The parameters of the best MLP and RBF networks for specific cutting force components (own study)

Id.	Network name	Quality (training) [%]	Error (training)	Activation (hidden)	Activation (output)
		Cutting force component F_x			
1	MLP 2-4-1	99.97	4.555	Logistic	Exponential
2	MLP 2-3-1	99.83	27.445	Tanh	Tanh
3	RBF 2-9-1	99.96	48.61	Gaussian	Linear
4	RBF 2-7-1	99.92	115.35	Gaussian	Linear
		Cutting force component F_y			
1	MLP 2-3-1	99.97	4.524	Logistic	Exponential
2	MLP 2-9-1	99.98	2.818	Logistic	Linear
3	RBF 2-7-1	97.83	322.578	Gaussian	Linear
4	RBF 2-9-1	98.52	220.881	Gaussian	Linear
		Cutting force component F_z			
1	MLP 2-8-1	99.96	9.726	Logistic	Exponential
2	MLP 2-3-1	99.95	9.942	Tanh	Linear
3	RBF 2-8-1	99.70	68.65	Gaussian	Linear
4	RBF 2-9-1	99.70	68.65	Gaussian	Linear

As a result of conducted neural network simulations of cutting force components emerging in AZ91HP milling, models for each component were developed on the basis of which component value could be determined. The figures below present the results of the cutting force component simulation depending on the cutting speed v_c and the feed per tooth f_z, taking into account the models of the highest quality and the most insignificant training error: F_x – a model of the neural network MLP 2-4-1 (Figure 3), F_y – MLP 2-9-1 (Figure 4) and F_z – MLP 2-8-1 (Figure 5). On their basis, it is possible to determine the value of individual force components for specific values of the cutting speed v_c and feed per tooth f_z. When the values v_c and f_z are entered into the Statistica programme, it provides the value of the adequate cutting force component.
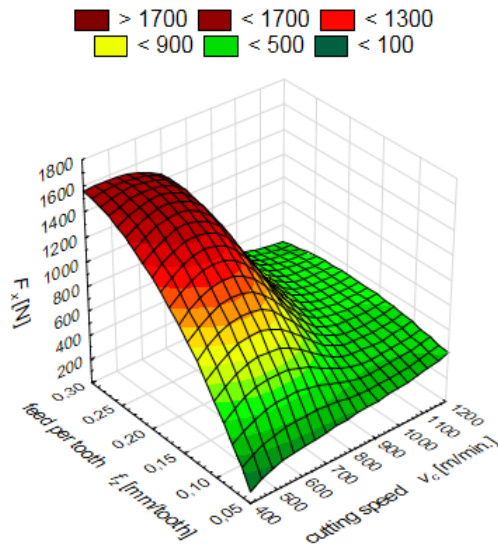
Fig. 3. The simulation results of the cutting force component F_x based on the cutting speed v_c and feed per tooth f_z for the neural network MLP 2-4-1 model (own study)
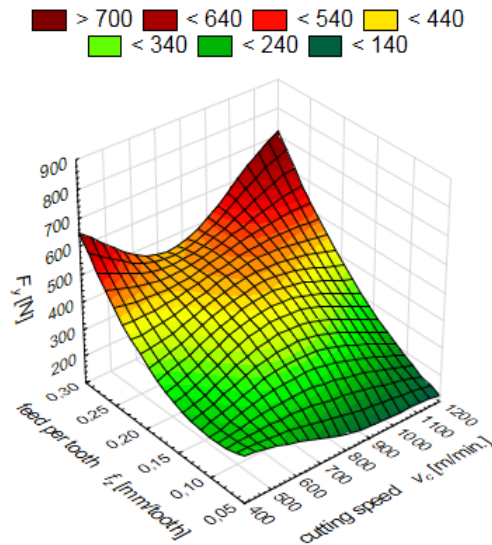

Fig. 4. The simulation results of the cutting force component F_y based on the cutting speed v_c and feed per tooth f_z for the neural network MLP 2-9-1 model (own study)
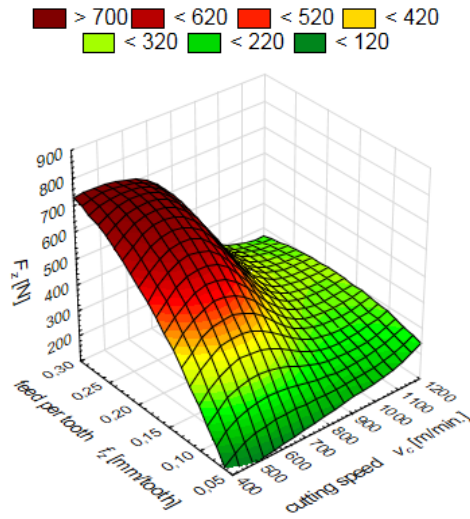
Fig. 5. The simulation results of the cutting force component F_z based on the cutting speed v_c and feed per tooth f_z for the neural network MLP 2-8-1 model (own study)

Models developed with the use of neural networks are a tool which allows specifying maximum values of the cutting force components. Modelling results can be of help to the technologists in determining technological parameters of machining. The simulation of the cutting force components can be employed for the creation of a computer system supporting technologist's decisions. In the presented study, the variable elements of the model were cutting speed v_c and feed per tooth f_z, whereas other parameters of the process such as cutting depth a_p, cutting width a_e, helix angle λ_s were constant.

4. SUMMARY AND CONCLUSIONS

It seems reasonable to conduct further research and simulations comprising solely variable parameters, which would enable application of models in a wider range of scenarios. The undertaken study will aim at increasing the number of vectors in a training sequence. In consequence, the representation of the actual functional relations presented by the model will be more accurate.

The results of the simulation create an opportunity to predict the non-linear processes. The simulations of such processes can be of considerable significance in a situation when little input data is available in relation to the need to obtain optimum results. Both the outcomes of the study and the simulations performed on their basis prove that there is a possibility to design a precise tool for modelling phenomena emerging during machining. The developed model enables testing various configurations of cutting parameters without the need to

perform machining tests, which are frequently laborious, time-consuming and requiring expensive practical testing. Initial determination of parameters and expected cutting force component values on the basis of simulation can reduce testing time for a new batch of products as well as allow economising on material, increasing the effectiveness and production capacity.

REFERENCES

Adamski, W. (2010). Manufacturing development strategies in aviation industry. *Advances in manufacturing science and technology*, *34*(3), 73-84.

Awrejcewicz, J. (2007). *Matematyczne modelowanie systemów*. Warszawa, Wydawnictwa Naukowo-Techniczne.

Cus, F., Zuperl, U., & Gecevska, V. (2007). High-speed milling of light metals. *Journal of Achievements in Materials and Manufacturing Engineering*, *24*(1), 357-364.

Danis, I., Monies, F., Lagarrigue, P., & Wojtowicz, N. (2016). Cutting forces and their modelling in plunge milling of magnesium-rare earth alloys. *International Journal of Advanced Manufacturing Technology, 84*(9-12), 1801-1820. doi:10.1007/s00170-015-7826-3

Fang, F. Z., Lee, L. C., & Liu, X. D. (2005). Mean Flank Temperature Measurement in High Speed Dry Cutting. *Journal of Materials Processing Technology*, *167*, 119-123. doi: 10.1016/j.jmatprotec.2004.10.002

Fu, Z. T., Yang, W. Y., Wang, X. L., & Leopold, J. (2015). Analytical Modelling of Milling Forces for Helical End Milling Based on a Predictive Machining Theory. *15th Cirp Conference on Modelling of Machining Operations (15th Cmmo), 31*, 258-263. doi:10.1016/j.procir.2015.03.013

Gziut, O., Kuczmaszewski, J., & Zagórski, I. (2014). The influence of technological parameters and geometric features of a cutting edge on cutting forces during AZ91HP alloy milling. *Advances in Manufacturing Science and Technology*, *38*(2), 83-92. doi: 10.2478/amst-2014-0013

Kim, J., & Lee, K. (2010). Surface Roughness Evaluation in Dry-Cutting of Magnesium Alloy by Air Pressure Coolant. *Engineering*, *2*, 788-792. doi: 10.4236/eng.2010.210101

Kuc, B. R. (2014, October 20). *Rola modelu i modelowania w pracy naukowej*. Retrieved from http://wydawnictwoptm.pl/blog/wp-content/uploads/2014/01/R.-B.-Kuc-Rola-modelu-i-modelowania.pdf

Kuczmaszewski, J., & Pieśko, P. (2013). Wpływ rodzaju powłok frezów węglikowych na siły skrawania oraz chropowatość powierzchni przy frezowaniu stopu aluminium EN AW-6082. *Mechanik*, *10*, 846-854.

Kuczmaszewski, J., & Pieśko, P. (2014). Wear of milling cutters resulting from high silicon aluminium alloy cast AlSi21CuNi machining. *Maintenance and Reliability*, *16*(1), 37-41.

Oczoś, K.E. (2000). Efektywne skrawanie stopów magnezu. *Mechanik*, *7*, 467-474. doi: dx.doi.org/10.17531/ein

Oczoś, K.E. (2009). Rozszerzenie granic stosowalności stopów magnezu. *Mechanik*, *5-6*, 386-400.

Pekguleryuz, M. O., Kainer, K., & Kay, A. A. (2013). *Fundamentals of Magnesium Alloy Metallurgy*. Elsevier.

Szaleniec, M. (2016, October 11). *Sieci Neuronowe i regresja wieloraka – czyli jak okiełznać złożoność w badaniach naukowych*. Retrieved from http://www.statsoft.pl/Portals/0/Downloads/Sieci%20neuronowe.pdf

Zagórski, I., & Kuczmaszewski, J. (2013). The study of cutting forces and their amplitudes during high-speed dry milling magnesium alloys. *Advances in Science and Technology – Research Journal*, 7(20), 61-66. doi: 10.5604/20804075.1073060

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A COMPARATIVE STUDY ON MULTI-SWARM OPTIMISATION AND BAT ALGORITHM FOR UNCONSTRAINED NON LINEAR OPTIMISATION PROBLEMS

Abstract

A study branch that mocks-up a population of network of swarms or agents with the ability to self-organise is Swarm intelligence. In spite of the huge amount of work that has been done in this area in both theoretically and empirically and the greater success that has been attained in several aspects, it is still ongoing and at its infant stage. An immune system, a cloud of bats, or a flock of birds are distinctive examples of a swarm system. In this study, two types of meta-heuristics algorithms based on population and swarm intelligence - Multi Swarm Optimization (MSO) and Bat algorithms (BA) – are set up to find optimal solutions of continuous non-linear optimisation models. In order to analyze and compare perfect solutions at the expense of performance of both algorithms, a chain of computational experiments on six generally used test functions for assessing the accuracy and the performance of algorithms, in swarm intelligence fields are used. Computational experiments show that MSO algorithm seems much superior to BA.

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1. INTRODUCTION

Optimization problems are ever-present in our daily life and often come in an array of forms. Ideally, Optimization is the activity of searching for the most favourable solution among a set of solutions to the problem based on some performance criteria. Optimisation problems are traditional and most widely studied problem in Combinatorial Optimization (Yang, 2008). Objective optimization (objective programming) is an area in computing that is concerned with mathematical optimization problems with defined decision making criteria, that involves some objective function to be optimized. In lots of technical fields, non linear objective optimization dealings in uninterrupted domains involve a costly numerical simulation with a varied objective function. Much of these problems can be found in broad applications as finance and logistics, manufacturing and in engineering. Practically, a crude solution to a continuous unconstrained optimisation problem will be meant to carry out a predefined task in some proficient way or the maximum quality or to generate maximum yields making reference to a given limited resource (Yuan, 2016).

Although not much research study has gone into single and multi-objective non linear optimization problems, most researchers have varied viewpoints and as a result, there exist diverse solutions and goals when defining and solving them. Though the paramount solutions can possibly be worked out by hand or through comprehensive search in some plain situations, programmed optimization techniques are needed to respond to most non-trivial problems largely due to their sizes and complex modality of the search space.

Unconstrained non linear optimization is a dynamic and fast rising research area with a greater impact in the real world. Regardless of the existence of a broad variety of such problems that may look relatively different from another, there are complete or approximate algorithms available to tackle like problems in complex situations. The process of fine-tuning optimisation can be likened to finding the highest peak of a landscape with little attention to the actual meaning of the problem as in fig 1.
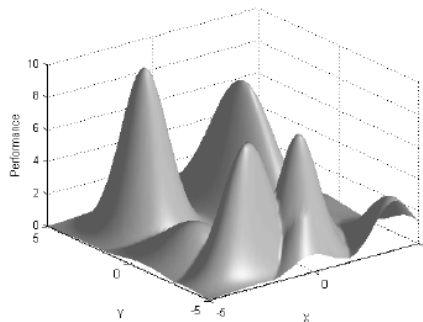

Fig. 1. Visualisation of optimisation problem (Yuan, 2016)

This paper makes use of two approximate algorithms, Multi Swarm Optimisation (MSO) and Bat algorithm (BA) for presenting a solution to the problem. Some authors claim these methods are generally termed meta-heuristic algorithms (Yang, 2008; Blum et al., 2008) although they are based on the intelligence of swarm. These methods dwell on the assurance of obtaining optimal solutions in practically limited time frame. Additionally, no gradient information is needed. This comes in handy in the situation of optimization problems which allows for the objective function to be given completely (that said, when objective function results are attained by simulation), or when there is non-differentiable objective function.

The paper aims to draw comparison between the Multi Swarm algorithm and Bat algorithm for solving continues unconstrained non linear single objective optimisation problems. The remains of the paper are arranged as follows. Section 2 in brief examines the non linear optimization mathematical models for experimenttation; Section 3 details brief explanation of the MSO and BA for testing and solving the problem. Experimental results are revealed in Section 4 and finally in Section 5 the conclusion of the work.

2. NON LINEAR OPTIMISATION PROBLEM

A Non-linear optimization problem is one in which in any case one of the constraints of the decision variable is a flat nonlinear function. Identified and researched in connection to sensitivity analysis, its original mention can be established from a thesis in 1952. In general optimisation problem may be defined mathematically by (Gal & Nedoma, 1972) as

$$P * (\theta) = \ min_{x \in \mathbb{R}^n} f(x, o) \tag{1}$$
$$g(x, \theta) \leq 0,$$
$$\theta \in \Theta \subset \mathbb{R}^m$$

where: x is the optimisation variable, θ are the parameters, $f(x, o)$ is the objective function, and $g(x, \theta)$ represent the constraints with Θ the parameter space.

A typical example of a Non-linear function description may take a form as:

$$2x_1^2 + x_2^3 + \log x_3 \tag{2}$$

where: x_1, x_2 and x_3 are decision variables.

Practically, the mathematical modelling of this problem may include variables that exponent to a number or a power, and/or multiplied or divided by some other variables. In most cases they make use of transcendental functions as exp, log, sine and cosine. A function is said to be multimodal if it has beyond one local optima. A variable function is separable if it can be modelled as one variable of a sum of functions. In this case the separability is directly correlated to the concept of epistasis or interrelation along with the variables of the function. Friedman (1994) presented a study on dimensionality problems and its features. Saibal et al (2012) undertake a study on Noisy Non-Linear Optimization Problems and made a comparative analysis of Firefly Algorithm and Particle Swarm Optimization. In the end, they concluded the superior-ability of firefly over particle swarm in solving noisy non linear optimisation problems.

In order to explore the difficulty of same problems behaviour of non linear optimisation problem, the next section of the paper considers six classical unconstrained Non-Linear optimization models taken from (*"Example Functions (single and multi-objective functions)",* 2016; *"Virtual Library of Simulation Experiments: Test Functions and Datasets"*, 2016) with its function definition and a 2D graphical representation.

2.1. Griewank Function

Griewank function has a lot of widespread local minima. Nevertheless, the position of the minima is frequently distributed. It has its global minimum value at 0 with the function initialization range from [−600,600]. Griewank function contain some product term that initiates interdependence with the variables.

$$f_1(x) = \sum_{i=1}^{n} \frac{x_i^2}{4000} - \prod_{i-1}^{n} cos\left(\frac{x_i}{\sqrt{i}}\right) + 1 \qquad (3)$$
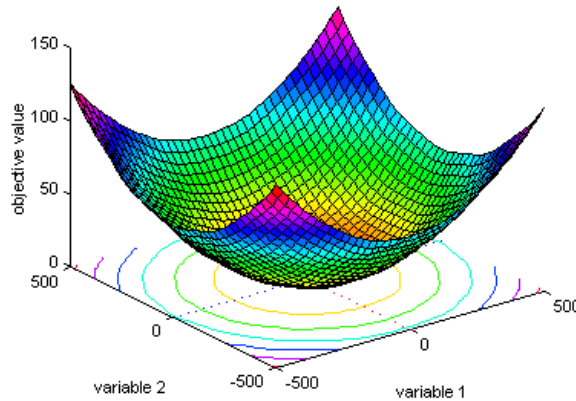

Fig. 2. 2D Plot for Griewangk's function ("Virtual Library of Simulation Experiments: Test Functions and Datasets", 2016)

2.2. Rastrigin function

Rastrigin function was modelled out of the Sphere function with a modulator cosine term to produce many local minima, thereby making the function highly multimodal. Its initialization range is between $[-15, 15]$. The contour of this function is made up of a great number of local minima where its value enlarges with the distance to the universal minimum.

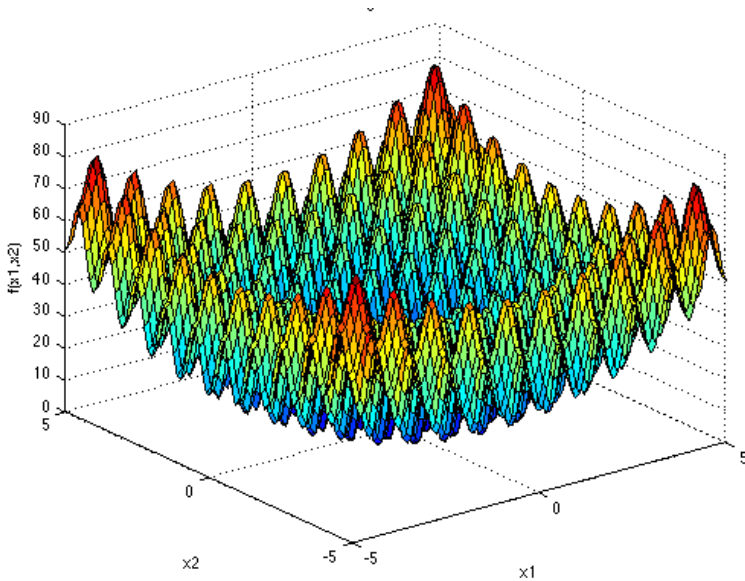$$f_2(x) = 10n + \sum_{i=1}^{n}(x_i^2 - 10\cos(2\pi x_i)) \tag{4}$$

Fig. 3. 2D plot for Rastrigin's function, ("Virtual Library of Simulation Experiments: Test Functions and Datasets", 2016)

2.3. Ackley Function

Ackley function has an exponential term that covers up its surface with many local minima. It is characterized by a nearly flat outer region, and a large hole at the centre. With an initialization range of $[-32.768, 32.768]$, the complexity of this function is moderated. Obtaining very fine results for the Ackley function revolves around applying an effective combination of exploratory and exploitative components in the search strategy. The function definition is stated in (5) with its plot in fig 4.

$$f_3(x) = -a\,exp\left(-b\sqrt{\frac{1}{d}\sum_{i=1}^{d} x_i^2}\right) - exp\left(\frac{1}{d}\sum_{i=1}^{d}\cos(cx_i)\right) + a + \exp(1) \quad (5)$$

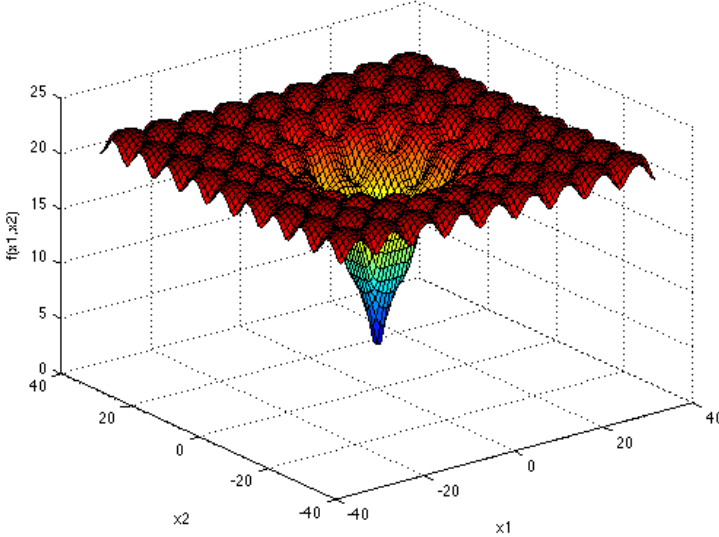where recommended variable values are: $a = 20$, $b = 0.2$ and $c = 2\pi$.

**Fig. 4. 2D plot for Ackely function ("Virtual Library of Simulation Experiments:
Test Functions and Datasets", 2016)**

2.4. Rosenbrock function

Rosenbrock function also known as banana or valley function is a traditional optimization problem with a duo dimensional function illustrating a deep valley having the form of a parabola of the shape $x_1^2 = x_2$ that results to the global minimum. Owing to the non-linearity of the valley, lots of algorithms congregate slowly since they vary the direction of the search constantly and for this reason this problem has been repetitively used in assessing gradient-based optimization algorithms performance. Valley function has an initialization range of $[-2.048, 2.048]$.

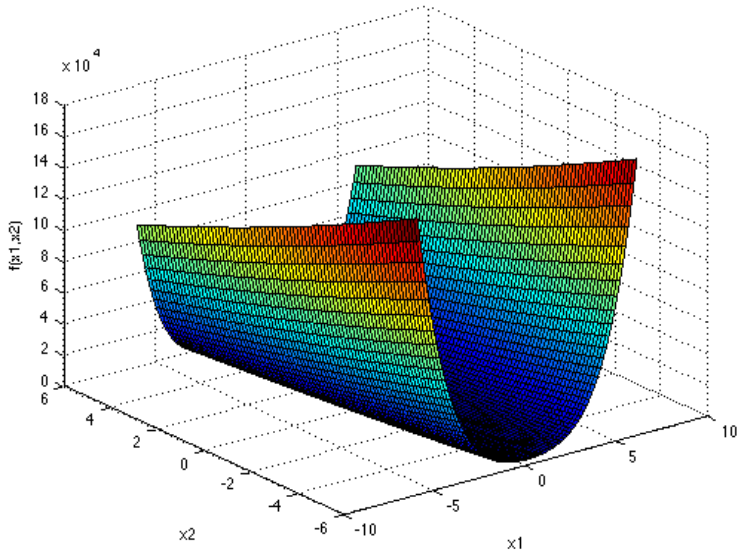$$f_4(x) = \sum_{i=1}^{n-1}[100.(x_{i+1} - x_i^2)^2 + (x_i - 1)^2] \quad (6)$$

Fig. 5. Plot for Rosenbrock function, ("Virtual Library of Simulation Experiments: Test Functions and Datasets", 2016)

2.5. Schwefel function

The Schwefel function is complex, with many local minima. Initialization range for the function is $[-500, 500]$. The surface of Schwefel function is made up of a large amount of peaks and valleys. It is a function which possesses two global minimum but the second best minimum stretches away from the global minimum that lots of search algorithms are shuttered in. The function is defined as:

$$f_5(x) = 418.9829d - \sum_{i=1}^{d} x_i \sin(\sqrt{|x_i|}) \tag{7}$$

In addition, the global minimum is close to the limits of the domain. The function has a minimum value of $2 * -418.9829 = -837.9658$ which is always hard to find because it is relatively far from the second best solution.
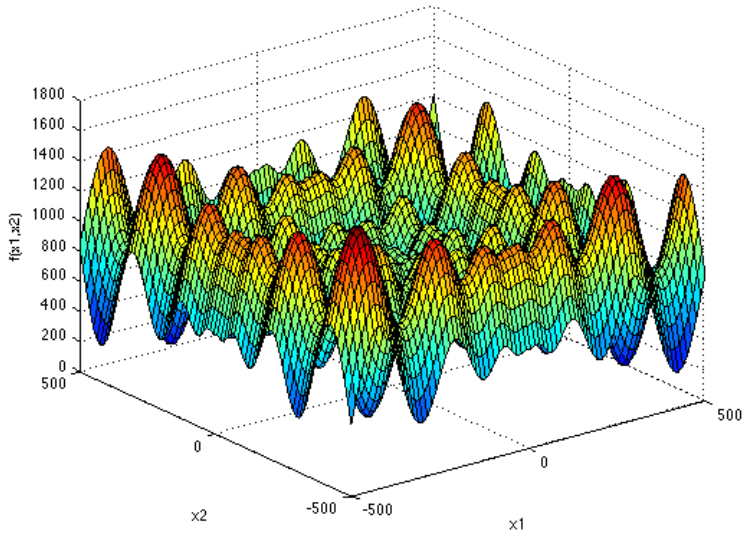
Fig. 6. 2D plot of Schwefel funtction (own study)

2.6. Michalewicz function

This function is multimodal with d! local optima. It has a parameter *m* which describes the "steepness" of the valleys or edges with larger m values leading to more complex search behaving like a needle in a haystack. This function is mostly used to test and check the efficiency of numerical optimization algorithms.

$$f_6(x) = -\sum_{i=1}^{d} \sin(x_i) \, sin^{2m}\left(\frac{ix_i^2}{\pi}\right) \tag{8}$$

Ideally, the suggested value of *m* = 10. The function illustration is defined as (8) with a 2D plot in fig. 7.
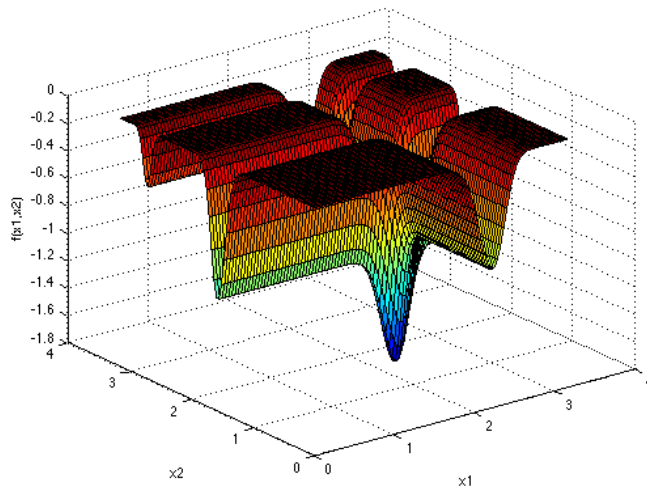
Fig. 7. 2D plot of Michalewicz function, ("Virtual Library of Simulation Experiments: Test Functions and Datasets", 2016).

3. META-HEURISTIC ALGORITHM

Meta-heuristic algorithms are increasingly being useful to solving complicated optimization problems and further to develop solutions to problems with complex nature in countless applications. This is probably due to their ability to handle difficult, ill-behaved, non-linear and multi-dimensional optimization problems as suggested by most researchers and practitioners with the latest of them demonstrated by Pansare and Kavade (2012), Madić et al. (2013), Zain et al. (2010), Ciurana et al. (2009), Rao et al. (2010), Samanta and Chakraborty (2011). In this study, an effort is made to compare the optimization results of two meta-heuristic algorithms applied to solving complex optimization problems, namely, Multi-Swarm optimisation and Bats Algorithm.

3.1.1. Multi Swarm Optimisation

Particle swarm optimization (PSO) has several extensions of which the Multi-swarm optimization is one. PSO mocks-up the activities of flocks such as that of birds and schools of fish. MSO do not rely on one (standard) swarm but rather fall on multiple sub-swarms practice (McCaffrey, 2016). The universal approach in multi-swarm optimization is that whilst a specific diversification process settles on where and when to initiate the sub-swarms, every sub-swarm centres on a specific region. MSO is meta-heuristic, in that the method has a set of design standards and procedures that can be used to create an explicit algorithm to solve a particular optimization problem. Since Multi-swarm optimization is an iterative

process, in its operation, it looks for a better solution, taking into consideration the best solution identified by any of the swarm particle until some stopping criteria is met. A characteristic feature of multi-swarms is that their preliminary positions and preliminary velocities are not arbitrarily selected as in particle swarms. As an alternative, they preserve some information from the earlier paths of the particles. In most cases, the improvement of multi-swarm systems guides to design decisions that on most occasions do not exist throughout the original growth of particle swarm optimization, for instance the number of particles to employ in every sub-swarm, the most favourable value for the check factor and the effects of logical starting positions and starting velocities. Having a clear identified guideline, these design decisions have been carefully revised with clear examples leading to the use of non-random primary positions and primary velocities to develop solutions in multi-swarm systems, which fail for single-swarms (Chen & Montgomery, 2011). Multi swarm optimization has been used to solve many optimization problems. MSO is applicable to solving several machine-learning situations, such as approximating the weights and bias figures of an artificial neural network or approximating the weights of frail learners in ensemble organization and prediction (McCaffrey, 2016).

Zhang and Ding (2011), suggested a multi-swarm self-adaptive and coopera-tive particle swarm optimization (MSCPSO). Their approach make use of four sub-swarms: with sub-swarms 1 and 2 being basic, sub-swarm 3 manipulated by sub-swarms 1 and 2, whereas sub-swarm 4 is influenced by sub-swarms 1, 2 and 3. In the end all four sub-swarms make use of a cooperative strategy. Although it attained good performances in fine-tuning complex multimodal functions, the approach fail in its application to practical engineering problems.

The activity of MSO which forms a key procedure in its operation is that of calculating for its particle new velocity (9). The velocity of a particle is being swayed by a number of factors such as: the present location of a particle, a particle best recognized location, the best recognized location of whichever particle in the same swarm as the particle and finally, the finest recognised location of whichever particle in any swarm. Equation (10) computes a particle new position after a new velocity has been identified

$$(t + 1) = w * v(t) + (c1 * r1) * (p(t) - x(t) + (c2 * r2) * \quad (9)$$
$$* \left(s(t) - x(t)\right) + (c3 * r3) * (m(t) - (x))$$

$$x(t + 1) = x(t) + v(t + 1) \quad (10)$$

where the term *v(t+1)* represent the new velocity, *v(t)* is the recent velocity, *x(t)* is the recent location, *p(t)* represent particle's best recognized location, *s(t)* is the finest location of any particle in the particle's swarm and the finest location of whichever particle in any swarm is *m(t)*. In addition to the definition of terms, inertia factor, *w* and *c1*, *c2* and *c3* are all constant with universal names

as cognitive, social, and global weights with $r1$, $r2$, and $r3$ being random values between 0 and 1 which present a randomization effect to every velocity update. Reasonable accepted values suggested by a number of particle swarm optimization researches presents 0.729, 1.49445, and 1.49445 for w, $c1$, and $c2$ respectively. The constant along with the random values and the inertia factor institute a maximum change for every component of the new velocity. Those constants decide to a large extent how each term influences the activity of a particle. Constant $c3$ is at its infancy in MSO and not much research has gone into it in obtaining a standard acceptable value.

One characteristic feature of Multi swarm optimisation technique is such that, a particle to be used may die and in such case, it needs to be substituted by a new particle at an arbitrary location, or it may immigrate such that in this case, the swarm is exchange with an arbitrarily chosen particle. The death and immigration instrument attach some element of uncertainty that help prevent the algorithm from returning non-optimal solution but a universal best solution. The next section outlines MSO algorithm.

3.1.2. Multi-Swarm Algorithm Pseudo-Code

Multi-Swarm Algorithm (McCaffrey, 2016) is one type nature-inspired heuristic algorithm which presents strong robustness and the ability to find optimal solution. The main steps of the algorithm are given below:

```
for each swarm iteration
    create particles at arbitrary locations
end for

whileas epoch < maximumEpochs iteration
  for-every swarm iteration
    for-every particle in swarm iteration

was particle dead?
    was particle immigrating?

calculate new velocity with concentration on
    current velocity, best particle location,
    best swarm location, and
    best overall location
  adopt new velocity to renew location
verify if new location is a new particle
    best, or a new swarm best, or
    a new universal best
  end every swarm
 end every particle
end while
return best universal location found
```

```
calculate new velocity with concentration on
        current velocity, best particle location,
        best swarm location, and
        best overall location

adopt new velocity to renew location
verify if new location is a new particle
        best, or a new swarm best, or
        a new universal best
    end every swarm
  end every particle
end while
return best universal location found
```

3.1.3. Bat Algorithm

The Bat algorithm (BA), a meta-heuristic algorithm is stimulated by the activities of bats for global optimization. It principles was inspired and developed in 2010 by Xin-She Yang. This algorithm is a multi-agent approach stimulated by the echolocation conducts of bats, with changing rates of pulse of emission and loudness, where a single pulse can last a little over thousandths of a second (ranging about 8–10 ms) (Altringham, 1996). Yet, the pulse has a continuous frequency which is more often than not in the range of 25–150 kHz which is equivalent to the wavelengths of 2–14 mm.

Yang identified three key features of the micro-bat to illustrate the fundamental structure of BA. These important characteristics as used by Yang are identified as follows (Yang, 2010):

I. Although greater numbers of species of bats make use of echolocation to hunt their prey, only a few fail to adopt this approach but may adopt another form of hunting technique. Conversely, the micro-bat is a renowned example of broadly using the echolocation technique. For this reason, the first characteristic is the behaviour of echolocation.

I. The frequency to which micro-bat transmits a predetermined frequency f_{min} with an inconsistent wavelength λ and the loudness A_o to look for prey.

II. Loudness by micro-bat can be regulated in several ways. Ideally, the loudness is believed to progress from an optimistic large value A_o to A_{min}, a minimum constant value.

Yang's method in simulations, make use of virtual bats in nature to identify the updated rules of their location x_i and velocities v_i in a D-dimensional search space. Fresh solutions x_1^t and velocities v_1^t at given time step t are obtained by

$$f_i = f_{min} + (f_{max} - f_{min})\,β,$$

$$v_1^t = v_1^{t-1} + (x_1^t - x_*)\,f_i, \tag{11}$$

$$x_1^t = x_1^{t-1} + v_1^t,$$

where f is the frequency the bat use in hunting for its prey, with the suffixes, min and max, standing for the minimum and maximum value, and $\beta \in [0, 1]$ represent the random vector obtained from a uniform distribution x_*, designate the present global near best solution which is obtained after evaluating all the results among all the n bats. A new solution for each bat is produced locally once a solution is chosen among the current best solutions, using random walk for the local search part. This is illustrated as:

$$x_{new} = x_{old} + \varepsilon A_t \qquad (12)$$

where $\varepsilon \in [-1, 1]$ = random number, $A_t = (A_i^t)$ represent the average loudness of every bat at the present time step.

The process is iterative therefore in addition, A_i, the loudness and r_i the pulse emission rate are renewed accordingly as the iterations progresses. These formulas are illustrated in equation 13.

$$A_1^{t-1} = \alpha A_i^t,$$
$$r_1^{t+1} = r_i^0[1 - \exp(-\gamma t)], \qquad (13)$$

Here α and γ are constants. For simplicity in Yang's experiments, $\alpha = \gamma = 0.9$ (Tsai et al., 2012). Per the idealization and approximations techniques employed, a summary of the basic steps of the bat algorithm is explained in the pseudo-code (Zhou et al., 2014).

```
Assume objective function f(x), x = [x₁,x₂,...,xₔ]ᵀ
Initialize the bat population xᵢ(I = 1, 2, ..., n) and vᵢ
Identify pulse frequency fᵢ at xᵢ
Initialise pulse rates rᵢ and the loudness Aᵢ
While (t < Max number of iterations)
        Generate new solutions by adjusting frequency,
        and updating velocities and locations/solutions
If (rand > rᵢ)
        Select a solution among the best solutions
        Generate a local solution around the selected solution
    end if
        Generate a new solution by flying randomly
If (rand < Aᵢ & f (xᵢ) < f (x∗))
        Accept the new solutions
        Increase rᵢ and reduce Aᵢ
end if
        grade the bats and find the recent best x∗
end while
        Post-process results and visualisation
```

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1. Parameters and Setting

The experimental settings is executed in Microsoft Visual C# 2010 version 10.0.3.319.1 RTMRel and carried out on a HP ProBook 4540s Computer with the processor of Intel(R) Core(TM) i3-3110M CPU at 2.40 GHz and 4096 GB memory. The general control parameters for both algorithms are the size of population and the number of maximum generation. The maximum numbers of cycles or generations used for the experiment is 1,000 with 6 dimensions (10, 15, 20, 25 and 30 and 35) of population size 25. The initialisation range [min, max] for all test functions are set to its global specific values.

Other specific control parameters and their values of the algorithms are presented in table 1.

Tab. 1. Parameter settings of algorithms (own study)

Multi Swarm Optimisation		Bats Algorithm	
Parameter Setting	Value/Range	Parameter Setting	Value/Range
Number of swarms	5	Initial Pulse, r_i^0	[0, 1]
Randomisation effect (r1, r2, r3)	[0, 1]	Initial loudness, A_i^0	[0.5, 2]
inertia weight w	0.729	$[f_{min}, f_{max})$	[0, 50]
cognitive, c1	1.49445	Random number, $\in$	[0, 1]
social, c2	1.49445		
global weight, c3	0.3645		
Death	0.001		
Immigrate	0.005		

4.2. Results and Findings

Tab. 2. Results obtained by BA and MSO Algorithms on f_1–f_6

Function	Algorithm Dim	BA		MSO	
		Value	Processing Time (ms)	Value	Processing Time (ms)
Griewank f_1	10	36.7378	24.7027	0.06151	411.6582
	15	149.251	27.6363	0.02464	560.5681
	20	159.262	25.5866	0.01232	690.3489
	25	299.961	28.2889	0.00000	858.6691
	30	265.519	30.7918	0.00000	995.7082
	35	427.209	30.3462	0.00000	1155.371
Mean Best		*222.99*	*27.89*	*0.0164*	*778.72*
Rastrigin f_2	10	351.313	22.999	0.00545	348.5491
	15	514.270	27.217	3.97984	487.8739
	20	709.450	29.992	11.9395	628.4436
	25	798.425	29.459	6.96471	764.1113
	30	886.754	30.810	17.9093	899.4347
	35	1429.693	30.708	37.8108	1041.189
Mean Best		*781.65*	*28.53*	*13.102*	*695.06*
Ackley f_3	10	18.9583	16.3993	0.00000	363.1926
	15	17.3149	28.6699	0.00000	505.2514
	20	19.5170	27.4071	0.00000	632.0096
	25	20.2093	28.9098	0.00000	772.8162
	30	19.9750	31.7634	0.00000	900.9023
	35	20.0563	32.1055	0.00000	1109.397
Mean Best		*19.338*	*27.543*	*0*	*713.93*
Rosenbrock f_4	10	26823760.1	21.0828	0.03984	291.2593
	15	23429221.4	26.007	0.44539	401.9415
	20	71148367.85	26.1592	0.28202	513.104
	25	94167522.53	29.5329	7.76763	613.4289
	30	131685159.98	32.0499	19.95645	711.3804
	35	155353591.25	28.117	25.03745	831.7191
Mean Best		*60464937.2*	*27.158*	*11.088*	*560.47*
Schwefel f_5	10	-79.3260	24.1545	-117.88	388.2503
	15	-98.2885	23.1431	-161.75	549.3576
	20	-109.9045	27.9776	-154.61	702.773
	25	-128.1006	23.5357	-171.96	912.7342
	30	-227.9366	30.6533	-354.54	1019.856
	35	-254.4494	34.9313	-398.49	1183.956
Mean Best		*-9.1676*	*27.399*	*-17984.54*	*792.82*
Michalewicz f_6	10	-3.7174	25.4515	-3.57858	536.9318
	15	-4.4228	24.2584	-3.96202	756.5302
	20	-4.9680	26.8576	-5.96101	990.6771
	25	-7.6216	27.1193	-6.46669	1202.339
	30	-7.8105	30.9676	-6.22626	1426.182
	35	-8.9912	35.9179	-8.39956	1659.426
Mean Best		*-6.2553*	*28.429*	*-5.7657*	*1095.3*

Fig 8 and 9 illustrates a graphical representation of the mean best value and time of the performance of the algorithms. From table 1.0 Bats algorithms performance on difficult functions such as Griewank and Ackley is on the downside.Functions with flat outer region with a large hole at its center seem to have no effect on MSO. MSO performance on these functions indicates its ability to moving out of the local minimum in the search space and locating the global minima. That said, MSO can converge to the minimum of both functions as dimensions increases. On Rosenbrock function, f_4, Bats algorithm returned very bad results which was far fetch from the global optima. Conversely MSO produce very good optimum solutions.

With regards to functions with deep valley with parabola shape, although MSO did return much better results in dimensions 10 and 15, later results obtain were a little larger. Bats algorithm on the other hand demonstrates its inability to return a better result returning largely very insignificant values with a flip flop approach (peaks and valleys). BA deteriorates substantially in its performance on this function than any other.
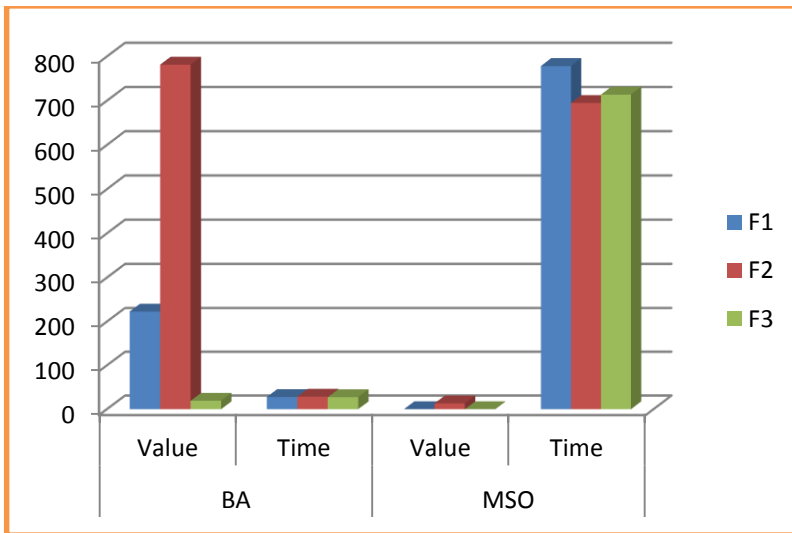

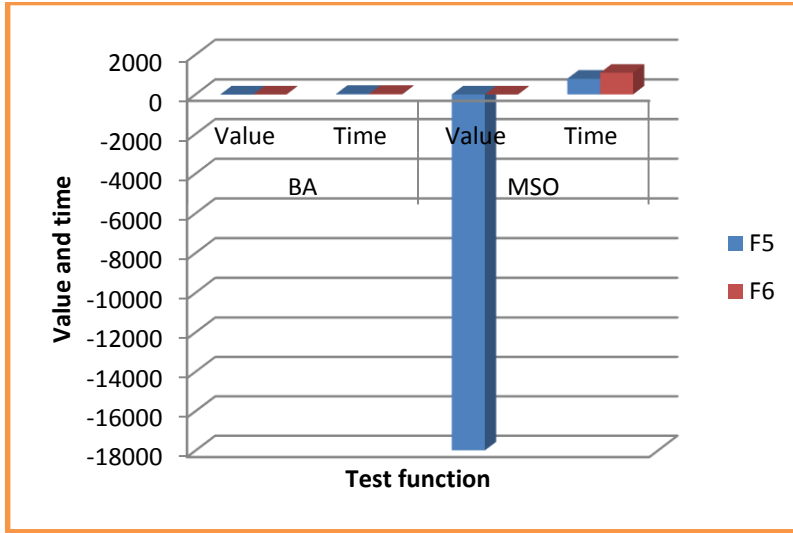**Fig. 8. Mean best value and time for f_1–f_3 by BA and MSO (own study)**

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Fig. 9. Mean best value and time for f_5 and f_6 by BA and MSOs (own study)

From the computational experiment, f_5 and f_6 demonstrated better convergence rate on both algorithms as they returned close to optimal solutions. As MSO outperforms BA at f_5, returning best results, BA on the other hand outperforms MSO at f_6. BA shows faster, better convergence rate and a demonstration on its effectiveness in testing optimisation problem than MSO.

On the whole, BA appears to be better in terms of computation process speed rate. This may possibly be due to the outcome from producing completely different arbitrary numbers to be used in the generation procedures of the algorithm. MSO outperforms BA in five non-linear optimisation problems experimented by returning better, optimum and close to optimal values. The searching ability of groups of swarm is very effective for local optimisation thus, the MSO algorithm success in exhibiting better performance on optimising multivariable and multimodal functions. This proof indicates the powerful potential of MSO in solving non-linear optimization problems.

5. CONCLUSION

In this paper, a comparative study of the performance of population based algorithms and swarm intelligence was undertaken. The target is to compare the performance of BA and MSO algorithm in fine-tuning continuous unconstrained non linear optimisation problem. With the intention of demonstrating the performance of both algorithms, they were exposed to six multi dimensional numerical multimodal benchmark functions. From the experimented

simulation results, the conclusion was that, the MSO algorithm out performs BA in returning optimal results although lags behind in processing time. MSO possessed the tendency to escape from the local minimum, so therefore can be used efficiently for multimodal and multivariable optimization. There are several gray areas which remain for future studies such as the exploration into the unique behaviour and characters of the bench mark functions on meta-heuristic optimisation algorithms and the effects of the parameters on the performance of the algorithms

REFERENCES

Altringham, J. D. (1996). *Bats: Biology and Behaviour*. Oxford University Press.

Blum, Ch., Roli, A., & Sampels, M. (2008). *Hybrid Metaheuristics. An Emerging Approach to Optimization.* Springer.

Chen, S., & Montgomery, J. (2011). Selection Strategies for Initial Positions and Initial Velocities in Multi-optima Particle Swarms. *Gecco-2011: Proceedings of the 13th Annual Genetic and Evolutionary Computation Conference*, 53-60.

Ciurana, J., Arias, G., & Ozel, T. (2009). Neural Network Modeling and Particle Swarm Optimization (PSO) of Process Parameters in Pulsed Laser Micromachining of Hardened AISI H13 Steel. *Materials and Manufacturing Processes, 24*(3), 358-368. doi:10.1080/10426910802679568

Example Functions (single and multi-objective functions). Retrieved August, 2016, from http://www.geatbx.com/docu/fcnindex-01.html#P150_6749

Friedman, J. H. (1994). An overview of predictive learning and function approximation. In V. Cherkassky, J. H. Friedman, & H. Wechsler (Eds.), *Statistics to Neural Networks. Theory and Pattern Recognition Applications. NATO ASI Series F* (pp. 1-61). Springer.

Gal, T., & Nedoma, J. (1972). Multiparametric Linear Programming. *Management Science Series a-Theory, 18*(7), 406-422. doi:10.1287/mnsc.18.7.406

Madić, M., Marković, D., & Radovanović, M. (2013). Comparison of meta-heuristic algorithms for solving machining optimization problems. *Mechanical Engineering*, *11*(1), 29-44.

McCaffrey, J. D. (2016, August). Multi-Swarm Optimization with C#. Retrieved from https://jamesmccaffrey.wordpress.com/2013/09/16/multi-swarm-optimization-with-c

Pal, S. K., Rai, C. S., & Singh, P. A. (2012). Comparative Study of Firefly Algorithm and Particle Swarm Optimization for Noisy Non-Linear Optimization Problems. *I.J. Intelligent Systems and Applications, 10*, 50-57. doi: 10.5815/ijisa.2012.10.06

Pansare, V. B., & Kavade, M. V. (2012). Optimization of cutting parameters in multipass turning operation using ant colony algorithm. *International Journal of Engineering Science & Advanced Technology*, 2(4), 955-960.

Rao, R. V., Pawar, P. J., & Davim, J. P. (2010). Optimisation of process parameters of mechanical type advanced machining processes using a simulated annealing algorithm. *International Journal of Materials & Product Technology, 37*(1-2), 83-101.

Samanta, S., & Chakraborty, S. (2011). Parametric optimization of some non-traditional machining processes using artificial bee colony algorithm. *Engineering Applications of Artificial Intelligence, 24*(6), 946-957. doi:10.1016/j.engappai.2011.03.009

Tsai, P. W., Pan, J. S., Liao, B. Y., Tsai, M. J., & Istanda, V. (2012). Bat Algorithm Inspired Algorithm for Solving Numerical Optimization Problems. *Applied Mechanics and Materials, 148-149*, 134-137. doi:10.4028/www.scientific.net/AMM.148-149.134

Virtual Library of Simulation Experiments: Test Functions and Datasets. Retrieved August, 2016, from https://www.sfu.ca/~ssurjano/optimization.html

Yang, X. S. (2008). *Nature-Inspired Metaheuristic Algorithms.* Luniver Press.

Yang, X. S. (2010). A new metaheuristic Bat-inspired algorithm. In J. R. González, D. A. Pelta, C. Cruz, G. Terrazas, & N. Krasnogor (Eds.), *Nature Inspired Cooperative Strategies for Optimization (NICSO 2010)* (pp. 65-74). Springer.

Yuan, B. (2016, August). A Brief Introduction to Global Optimization. Retrieved from http://boyuan.global-optimization.com/optimization.htm

Zain, A. M., Haron, H., & Sharif, S. (2010). Application of GA to optimize cutting conditions for minimizing surface roughness in end milling machining process. *Expert Systems with Applications, 37*(6), 4650-4659. doi:10.1016/j.eswa.2009.12.043

Zhang, J. Z., & Ding, X. M. (2011). A Multi-Swarm Self-Adaptive and Cooperative Particle Swarm Optimization. *Engineering Applications of Artificial Intelligence, 24*(6), 958-967. doi:10.1016/j.engappai.2011.05.010

Zhou, Y. Q., Xie, J., Li, L. L., & Ma, M. Z. (2014). Cloud Model Bat Algorithm. *The Scientific World Journal, 2014*. doi:10.1155/2014/237102

Bogna MRÓWCZYŃSKA[*]

COMPARISON OF PARETO EFFICIENCY AND WEIGHTED OBJECTIVES METHOD TO SOLVE THE MULTI-CRITERIA VEHICLE ROUTING PROBLEM USING THE ARTIFICIAL IMMUNE SYSTEM

Abstract

The solutions to the multi-criteria vehicle routing problem, dependent on route length and travelling time of delivery van, are presented in the paper. This type of problem is known as a traveling salesman problem. The artificial immune system is used to solve it in this article. Since there are two variables – route length and travelling time – two methods are employed. They are: Weighted Objectives Method and Pareto Efficiency Method. The results of calculation are compared.

1. INTRODUCTION

A major challenge in the distribution of goods is finding the optimal vehicle routes. Most often optimization seeks to minimize the number of kilometers, which primarily are translated into fuel and maintenance costs. Travelling time is also important because of drivers' wages, quick and timely delivery of goods to the customer, and consequently it affects customer satisfaction. The emissions, which recently have become more stringent, rely on such parameters as the age of vehicles, route length and individual driving styles. Optimization of vehicle routes is dependent on many variables. This paper presents how to optimize delivery schedule from one warehouse to multiple vendors.

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The controlled variables are: distribution of goods to a specified number of locations using one delivery van in one day. For such a scenario calculations were made using both methods.

2. TASK FORMULATION

From a mathematical standpoint, the travelling salesman problem is to find the shortest route that passes through each of a set of points.

To solve the traveling salesman problem, one of the known methods can be used. The solution offered by the construction of the Hamilton cycles in the graph representing the network of roads and finding the best one is possible only for small graphs. Therefore, the other methods are used. The branch and bound method is very popular and recently supported by artificial intelligence methods (Karaoglana et al., 2011). The genetic or evolutionary algorithms (Król, 2017), k-means methods (Ambroziak & Jachimowski, 2012), neighborhood search (Kytöjokia et al., 2007) and others heuristic methods are applied successfully. However, this approach uses artificial immune system. Optimization, which simultaneously takes into account the roadway and time is important for route delivery planning with varying traffic patterns. In this case, the travel time is a nonlinear function of the road and it should be taken into account as the independent variable.

There are many methods of multi-criteria optimization (Kovács & Bóna, 2009). Presented calculations use two different approaches to find the solution to the problem of multiple-criteria: weighted objectives method and Pareto efficiency.

2.1. Weighted Objectives Method

Weighted objectives method is used often to solve multi-criteria problems. In the case of minimizing road and travel times optimization criteria can be expressed in the following objective function:

$$\mathbf{f}: \mathbb{D} \subset \mathbb{N}^m \rightarrow \mathbb{R} \tag{1}$$

where: $\mathbb{D} = \{x=(n1, n2, \ldots nm): \forall i \in N, i \leq m\ ni \in \mathbb{N}\}$ – an acceptable set of all possible routes being held by m points of receipt of goods,
$\mathbb{R}$ – a set of real values of objective function.

In the method of the weighted objectives the functions expressing the criteria are linked using weighted coefficients as follows:

$$\mathbf{f}: (n_1, n_2, \ldots n_m) \rightarrow w_1 f_1 + w_2 f_2 + \ldots w_n f_n \qquad (2)$$

where: f_i – criteria, i=1, … n,

$\quad$ n – number of criteria,

$\quad$ w_i – weighted coefficients; i=1, …n; often it assumes that

$$\sum_{i=0}^{n} w_i = 1 \qquad (3)$$

As a result, multi-criteria task is reduced to one-criteria, which can be solved by the methods used to optimize one objective function.

In the case where the minimization of the road is the first criterion, and a travel time is a second, the objective function has the following equation:

$$f = w_1 \frac{d_{oi_1} + \sum_{k=1}^{m-1} d_{i_k i_{k+1}} + d_{i_m 0}}{d_{max}} + w_2 \frac{t_{oi_1} + \sum_{k=1}^{m-1} t_{i_k i_{k+1}} + t_{i_m 0}}{t_{max}} \qquad (4)$$

where: m – number of delivery points,

$\quad$ 0 – warehouse,

$\quad$ $\{i_1, i_2, \ldots, i_m\}$ – a sequence of points in the order of service,

$\quad$ d_{ij} – the shortest distance form i-th point to j-th point,

$\quad$ t_{ij} – the shortest travel time form i-th point to j-th point,

$\quad$ w_1, w_2 – weight coefficients,

$\quad$ d_{max} – the maximum route length estimated in advance,

$\quad$ t_{max} – the maximum travel time estimated in advance.

In the weighted objectives method, the selection of appropriate weight coefficients may be of a problem since manipulating them is subjective. It calls for assigning a dominant criteria in a situation where all of them are equal.

2.2. Pareto efficiency

Pareto efficiency is the other method of solving the problem. It is frequently used in applications of genetic and evolutionary algorithms. The models described in (Goldberg, 1989) were followed to perform calculations presented in this paper.

Pareto optimality is a state where the improvement of one criterion has a negative impact on another one. In the case of minimization, a solution not dominated is defined as:

$$\mathbf{f^*}=(\mathbf{f_1}, \ldots, \mathbf{f_m}): \qquad \forall_{i\in\mathbb{N}}\, \mathbf{f_i^*} \le \mathbf{f_i} \wedge \exists_{j\in\mathbb{N}}\, \mathbf{f_j^*} < \mathbf{f}_j \qquad (5)$$

which means that the function $\mathbf{f}$ is dominated by $\mathbf{f^*}$ ($\mathbf{f^*} \prec \mathbf{f}$).

A set of non-dominated solutions is called the Pareto front. The best solution is selected from the Pareto front. In the case of minimizing road and travel time optimization criteria can be expressed in the following objective function:

$$\mathbf{f}: \mathbb{D}\subset \mathbb{N}^{\,m} \rightarrow \mathbb{R}^2 \qquad (6)$$

where the meanings are as in formula (1). To put it differently an objective function is the following mapping of:

$$\mathbf{f}: (n_1, n_2, \ldots n_m) \rightarrow (s, t) \qquad (7)$$

where: s – the distance between the pickup points in the order given,
         t – the time needed to cover the selected option.

In terms of numerical solutions, pairs are searched (s*, t*) such as

$$\forall (s, t) \in \mathbb{R}^2 \, \exists \, s^* \in \mathbb{R}: s^* \le s \vee \exists \, t^* \in \mathbb{R}: t^* \le t \wedge (s, t) \neq (s^*, t^*) \qquad (8)$$

3. NUMERICAL MODEL

3.1. Clonal Selection

In this model artificial immune system has been utilised to designate routes for deliveries.

The artificial immune system is one of the methods of artificial intelligence which has been inspired by the human immune system (Wierzchoń, 2001). This network is activated when foreign antigens invading an organism have overcome the body's mechanical barriers such as the skin, mucus membranes, and the cornea.

When antigens get into the bloodstream they are captured by antibodies. In order to remove antigens, first they must be physically immobilized. This involves the reshaping of the antibody to bind to the antigen. Then antibodies are mutated. These antibodies, which are best matched to the antigen, are abundantly cloned and with the blood penetrate throughout the body in search of the enemy.

Captured antigens are destroyed, but the way in which this takes place is no longer essential for the numerical model. When antigens do not threaten the body any longer, the antibody population is suppressed. The patterns to diagnose the next attack are stored in the body. This simplified model of recognition of antigen presented here is called a clonal selection and it is a paradigm of clonal selection of artificial immune system.

3.2. Artificial Immune System

Numerical algorithm imitating the clonal selection can be described by first defining:
antigen – the optimum solution for the task,
antibody – an approximate solution,
affinity – measure of fitting an antibody to the antigen – the value of the objective function for a given solution,
population of antibodies – a finite set of different solutions,
cloning – copying existing solutions,

mutating – mapping $\mathbb{M}$: $(n_1, n_2, \dots n_m) \longrightarrow (n_{1j}, n_{2j}, \dots n_{mj})$, which changes the order of selected points n_j.

The steps of the algorithm are as follows: at first, the random population of antibodies is generated and an affinity of antibodies is evaluated.

Next the best fitted antibodies are cloned and mutated. Each mutated antibody is evaluated. The best antibodies pass to the next generation. The rest is eliminated in the process of suppression. Everything is repeated until the condition to stop the calculation. A flowchart of clonal selection is shown in Figure 1.

The evaluation of the affinity, important in this algorithm, depends on the accepted criterion. The route length and the travel time are determined for each solution in every method of optimization. These parameters are substituted into the formula (3) in weighted objectives method for calculating the affinity.

The affinity rating in the case of Pareto optimal solutions requires consideration of some steps of the algorithm (Figure 1) of the substeps as described in Figure 2.
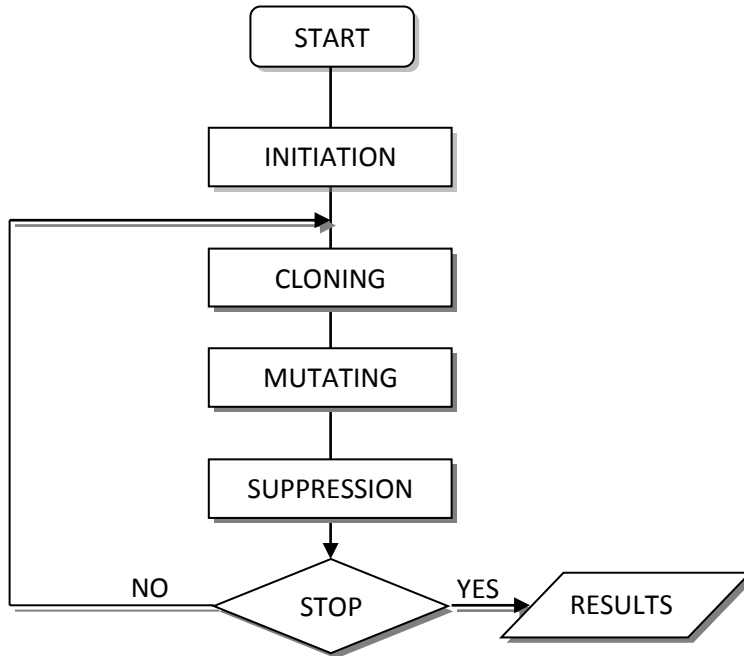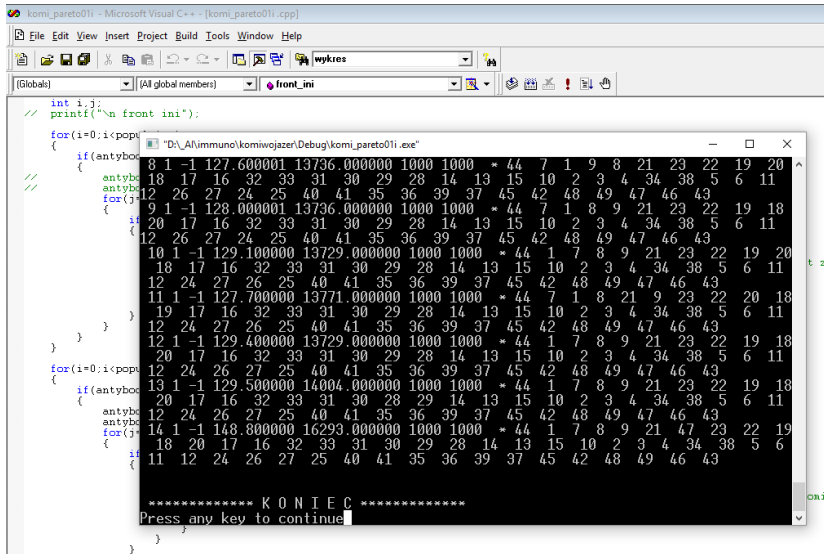
Fig. 1. Clonal selection's algorithm (own study)

1. In the entire population of antibodies all individuals not dominated are searched (Pareto front) and the highest rank is assigned to them.
2. In a subpopulation consisting of the remaining antibodies another Pareto front is determined and antibodies from it receive a lower rank.
3. The substep 2 is repeated until each antibody from the population receives a rank.
4. Antibodies are subjected to cloning. Number of clones is directly proportional to the rank of the antibodies.
5. In the process of the suppression, the antibodies are eliminated sequentially starting from the lowest ranks.

Fig. 2. Clonal selection algorithm – Pareto optimality (own study)

4. CALCULATION
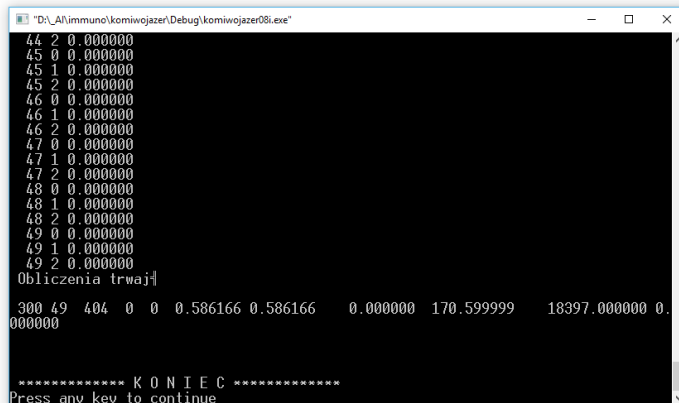
The calculations of Pareto optimality was made using komi_pareto01i.exe (Figure 3).

Fig. 3. The window of komi_pareto01i.exe with the end results (own study)

Komiwojazer08i.exe was used for calculations by the weighted objectives method (Figure 4).

Fig. 4. The window of Komiwojazer08i.exe with the end results (own study)

Komi_pareto01i.exe and komiwojazer08i.exe are own implementations of Artificial Immune System in C++ .

As already mentioned, the purpose of the calculation is to obtain the shortest route and the quickest time of delivery from a warehouse to customers. On a selected day the warehouse is required to deliver goods to 49 recipients using one van. There is no time limit. The shortest distance and travel time between collection points are available. Table 1 shows the distance and transit times.

Tab. 1. The distance and transit times for each edge of the graph (own study)

No. edge	the beginning of the edge	the end of the edge	distance [km]	Travel time [s]	No. edge	the beginning of the edge	the end of the edge	distance [km]	Travel time [s]	No. edge	the beginning of the edge	the end of the edge	distance [km]	Travel time [s]
1	1	3	0,8	88	34	14	32	4,3	345	66	48	45	4,8	713
2	1	2	1	99	35	32	33	1,7	139	67	47	49	2	323
3	2	10	3	304	36	31	33	3,6	261	68	46	47	2,8	325
4	1	9	2,1	216	37	31	32	4,4	344	69	43	46	2,6	372
5	1	7	2,2	254	38	29	32	2,7	178	70	46	48	4,1	535
6	1	44	3,1	435	39	27	30	5,6	380	71	43	44	2	254
7	1	43	4,6	625	40	26	27	2,1	162	72	44	50	1,2	182
8	1	42	3,1	381	41	24	26	2,9	220	73	22	50	3,8	532
9	2	5	2,1	272	42	24	29	4,3	308	74	8	17	2,9	345
10	3	5	2,2	285	43	12	28	2,9	227	75	17	19	1,3	180
11	3	4	0,6	80	44	12	24	2,5	151	76	19	22	2,2	256
12	4	5	2	236	45	24	25	2,2	136	77	21	22	1,9	247
13	2	9	2,6	351	46	25	39	6,9	444	78	17	18	2	300
14	2	8	2,8	349	47	10	11	3,4	192	79	8	10	2,1	250
15	8	9	1,2	139	48	11	12	1	63	80	43	50	2	238
16	8	21	1,8	251	49	6	11	3,9	323	81	23	44	2,3	331
17	9	21	0,7	100	50	5	10	4,1	503	82	43	48	6,2	481
18	7	9	2	247	51	5	6	2	254	83	47	48	5,7	716
19	9	23	1,1	146	52	6	38	3,8	433	84	49	48	4,8	581
20	21	23	1,5	211	53	5	38	2,5	333	85	42	48	1,7	205
21	22	23	1,2	198	54	4	38	3	352	86	42	45	2,4	288
22	20	22	3,2	471	55	4	34	2,1	235	87	34	45	4,5	575
23	19	21	3,2	407	56	34	38	1,5	143	88	38	41	7,5	572
24	19	20	1,5	202	57	36	39	3,8	479	89	35	41	5,1	473
25	18	20	1,6	178	58	35	36	2	252	90	40	41	6,1	766
26	18	19	1	108	59	35	39	3,2	478	91	36	40	2,5	313
27	16	18	1,6	183	60	37	39	1,8	236	92	16	32	4,1	335
28	16	17	1,2	139	61	35	37	2	247	93	13	32	3,1	255
29	15	17	3,8	307	62	37	38	2	329	94	11	28	2,6	195
30	10	15	1,1	76	63	37	6	5,9	683	95	28	29	2,4	160
31	13	28	3,2	230	64	38	45	3,3	411	96	29	30	1	70
32	13	15	1	106	65	45	49	1,5	202	97	12	25	6,2	393
33	13	14	1,6	178										

The calculation results for the method of weighted criteria, and for Pareto optimality are listed in Table 2. Despite using coefficients in a function (3) which according to the experience of the author were well matched, the results of Pareto optimal solution are much better. As you can see the both solutions of weighted objectives method are dominated by solutions of Pareto efficiency method. Both solutions of Pareto optimality do not dominate each other. In the first solution, the road is shorter than in the other one, and in a second travel time is less than in the first solution.

Tab. 2. The best results of the calculation (own study)

	route length	travel time [s]	The sequence of points in the order of service																
Weighted Objectives Method	150,2	16305	0	43	44	7	9	8	21	22	23	1	2	5	6	11	12	28	29
			30	31	33	32	16	18	20	19	17	15	13	14	24	25	26	27	10
			3	4	34	38	45	49	47	46	48	42	35	41	40	36	39	37	0
	147,8	15235	0	43	44	23	9	21	22	19	20	18	16	17	8	2	1	3	4
			34	38	45	49	47	46	48	42	10	13	14	15	5	6	37	39	25
			24	12	11	28	29	32	33	31	30	27	26	40	36	35	41	7	0
Pareto Efficiency	129	13729	0	44	1	7	9	8	21	23	22	19	20	18	17	16	32	33	31
			30	29	28	13	14	15	10	2	3	4	34	38	5	6	11	12	24
			27	26	25	40	41	35	36	39	37	45	42	48	49	47	46	43	0
	127,5	13736	0	44	7	1	8	9	21	23	22	20	18	19	17	16	32	33	31
			30	29	28	13	14	15	10	2	3	4	34	38	5	6	11	12	26
			27	24	25	40	41	35	36	39	37	45	42	48	49	47	46	43	0

The solution to the problem using each of the methods has been achieved in a similar, very short computational time. It can therefore be expected that the use of Pareto optimality in further calculations will give good results too.

5. CONCLUSIONS

The Pareto optimality method used to plan the shortest and fastest route of the delivery van is effective and as fast as the method of weighted factors. Pareto optimal solutions are better than those obtained with the weighted objectives method, despite using the coefficients that have been tested in this type of calculation.

The chosen example is a simplified fragment of a larger, more complex, with restrictions on the delivery time and takes into account the varying intensity of movement. Results of calculations encourage the author to use the Pareto optimality method to solve this bigger example and in further studies.

REFERENCES

Ambroziak, T., & Jachimowski, R. (2012). Algorytm klasteryzacji w zastosowaniu do problemu trasowania pojazdów. *Logistyka*, *2*, 337-342.

Goldberg, D. E. (1989). *Genetic algorithms in search, optimization, and machine learning*. Boston: Addison-Wesley Pub. Co.

Karaoglan, I., Altiparmak, F., Kara, I., & Dengiz, B. (2011). A branch and cut algorithm for the location-routing problem with simultaneous pickup and delivery. *European Journal of Operational Research, 211*(2), 318-332. doi:10.1016/j.ejor.2011.01.003

Kovács, G., & Bóna, K. (2009). Applying a multi-criteria decision methodology in the implement-tation of tenders for the acquisition of the infrastructure of logistics systems. *Periodica Polytechnica Transportation Engineering, 37*(1-2), 39-44. doi: 10.3311/pp.tr.2009-1-2.07

Król, A. (2017). Application of the genetic algorithm for optimization of the public transportation lines. In G. Sierpiński (Ed.) *Advances in Intelligent Systems and Computing (vol. 505, pp. 135 – 146).* Springer.

Kytojoki, J., Nuortio, T., Braysy, O., & Gendreau, M. (2007). An efficient variable neighborhood search heuristic for very large scale vehicle routing problems. *Computers & Operations Research, 34*(9), 2743-2757. doi:10.1016/j.cor.2005.10.010

Wierzchoń, S.T. (2001). *Sztuczne systemy immunologiczne. Teoria i zastosowania.* Warszawa: Akademicka Oficyna Wydawnicza Exit.

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COMPUTER ANALYSIS
OF ELECTROMOTORIC SWIVEL WALKER
MOVEMENT

Abstract

The first mechanical construction of swivel walker is from year 1963 and it was aimed for support movement of people with disabilities. This solution was very difficult and it was main reason for purpose of electromotoric module, which facilitates movement and reduce effort of people with disabilities. Therefore further research in this area are still provided. In this paper trajectory of swivel walker with electromotoric modules is described. To analyze the tilt and trajectory structure of the walker SolidWorks software was implemented.

1. INTRODUCTION

Movement with mechanical swivel walker is physically demanding and for this reason we prepared a swivel walker design with electromotoric modules to facilitate a movement for handicapped. This model consists of base platform, pylon, couple of rocking plates (foots) and electromotoric modules. The man has to move his weight (CoG) to one rocking plate and then the second rocking plate together with base platform is turned round the vertical axis of first rocking plate employing only inertial force. Every rocking plate is able to rotate round of the pylon vertical axis. Rotation is stopped after the limit position of the rocking plate is reached (limit stop) in each direction and the rocking plate is returned back to the initial position by the force of spring.

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2. SOLUTION WITH ELECTROMOTORIC MOVEMENT TO FORWARD

From analysis of deficiencies of mechanical swivel walkers focus for ideal function was create proposal of electromotoric module for swivel walker shown on fig. 1 (Butler et al., 1982; May et al., 2004; Stallard et al., 2003).
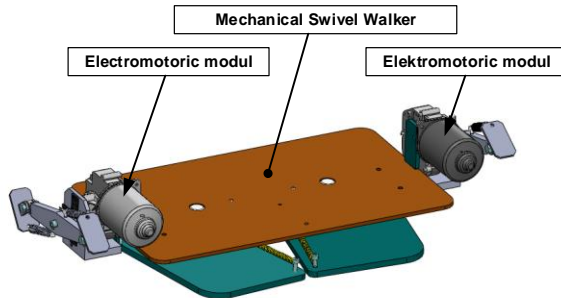

Fig. 1. Swivel walker with electromotoric modules (own study)

The principle of mechanism walking is based on a mechanical feed, where rate is limited by mechanical backstop and long of spring, fig. 2.
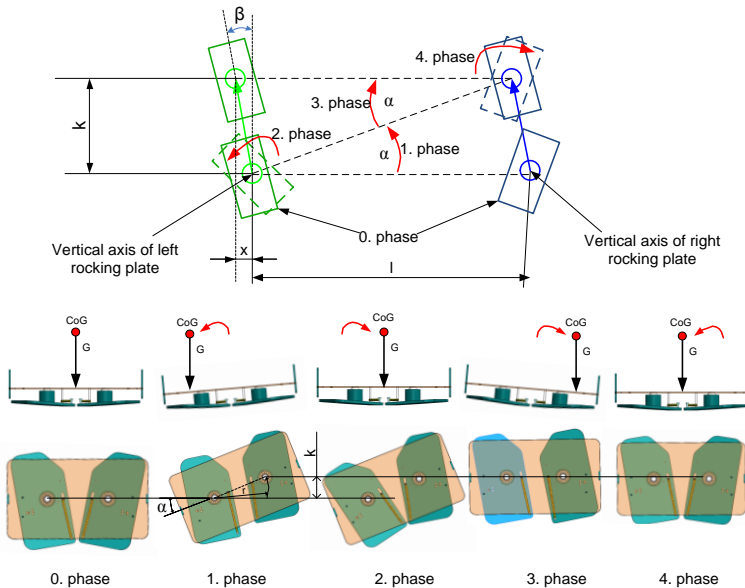

Fig. 2. Phases of movement to forward (own study)

As the driving force of mechanism is used shift of the human CoG to the right or left side. Tilt of mechanism construction is limited by the chamfer of rocking plates. Angle between rocking plates and ground has value θ. This angle and sufficiently large area of the rocking plates prevents overbalance of the whole complex (Knoflíček & Haltmar, 2000; Kaňuch, 2007).

3. TILTING SIMULATION

To determine stability is important to set a degree of structure tilting and height level of subject CoG (Świć at al., 2012; Świć at al., 2014). For this reason was done computer simulation in SolidWorks where we were interested in tilting structure trajectory (Baláž & Sukop, 2005; Čirip & Hajduk, 2010; Hajduk, 2007; Hajduk et al., 2005).

Input parameters for simulation were equipment design and motor speed 10 rpm. Progress of simulation is shown in next pictures split into three stages.

In the stage 0 shown on fig. 3, equipment is in initial position, when the tilting structure is in horizontal position in an angle $\gamma 0$. Central point of the tilting structure (arm) is in the height level $z0$ above the base.
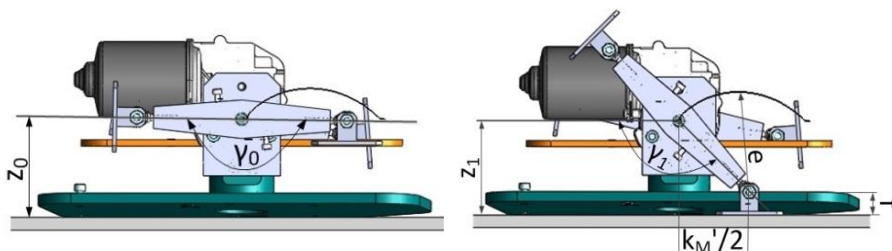

Fig. 3. Zero stage and first stage of tilting simulation (own study)

In the stage 1 shown on fig. 3, stopper of the tilting structure is in contact with the base. There is known distance between axis of stopper and axis of central point of the tilting structure in horizontal position $kM'/2$, height level of stopper f and vertical height level of center of tilting structure above base $z1=z0$. In the stage 2 shown on fig.4, tilting structure is in vertical position and left rocking plate is with all surface in contact with the base and center point of tilting structure according to curved path is in the height level $z2$ above base. In this stage equipment is in the middle of the cycle.
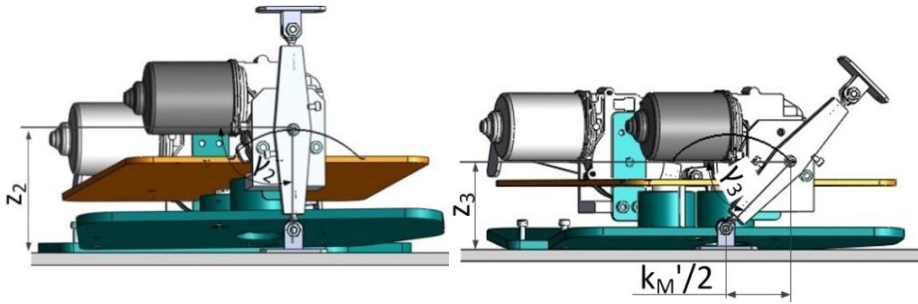
Fig. 4. Second and third stage of tilting simulation (own study)

Followed the length of tilting structure shown on fig. 5 is calculated from the center point to the stopper axis where an equipment is tilted in the angle β.
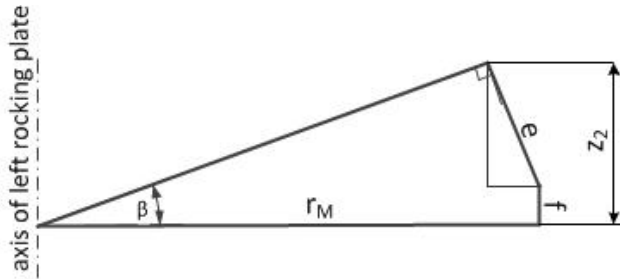

Fig. 5. Length of tilting structure (own study)

Calculating of the tilting structure e:

$$z_2 = r_M \times tg\beta \tag{1}$$

where: z_2 is height of axis of motor and base,
r_M is radius of stopper via axis of left rocking plate,
β is angle via base plane and height of axis of motor,

$$e = \frac{z_2 - f}{\cos \beta} \tag{2}$$

where: e is length of tilting structure,
f is height of base and axis of stopper.

In the stage 3 (Fig. 5) equipment is in the end of tilting cycle and both rocking plates are touched with inner edges in contact with base.

2.1. Results of tilting simulation

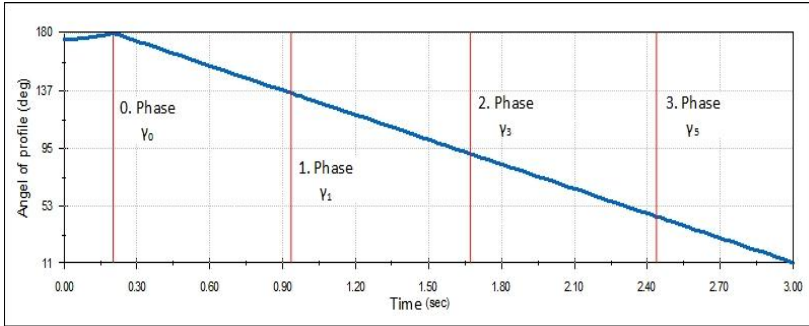At first graph is shown the rotary angle of arm in all phases, fig. 6.

Fig. 6. Process of arm rotary angle (own study)

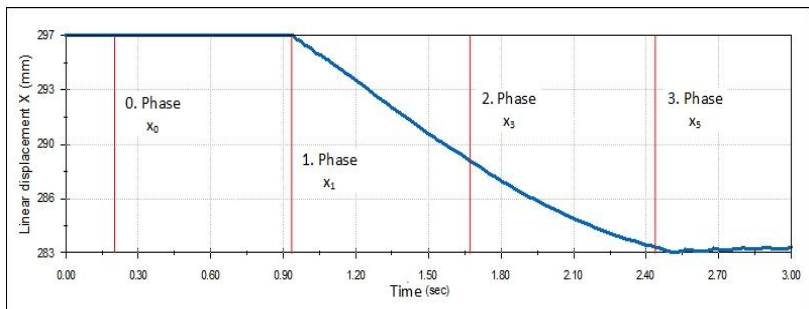At second graph is shown linear displacement axis of motor in X plane over the cycle, fig 7.

Fig. 7. Process of linear displacement axis of motor in X plane (own study)

At third graph is shown linear displacement axis of motor in Yplane over the cycle, fig. 8.
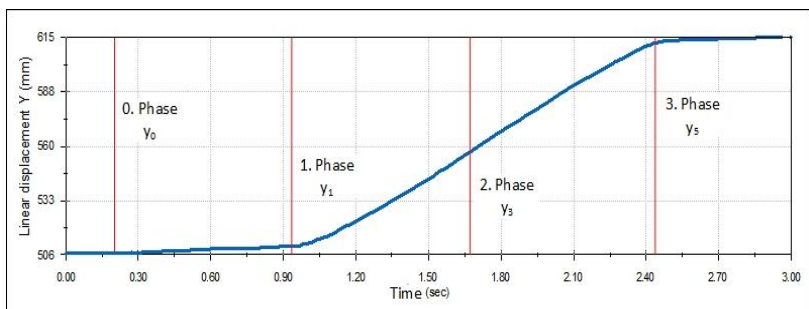
Fig. 8. Process of linear displacement axis of motor in Y plane (own study)

At fourth graph (fig. 9) linear displacement axis of motor in Z plane over the cycle with high difference z3-z1 or z3-z5 is shown.
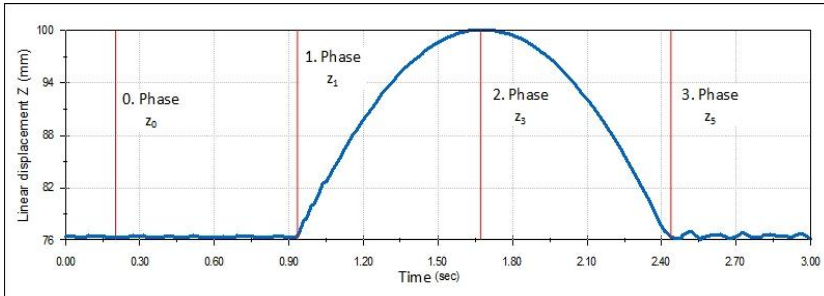

Fig. 9. Process of linear displacement axis of motor in Z plane (own study)

Product of simulation, shown on fig. 10, is 3D trajectory chart of tilting structure center point movement in 3D for time t = 3s.
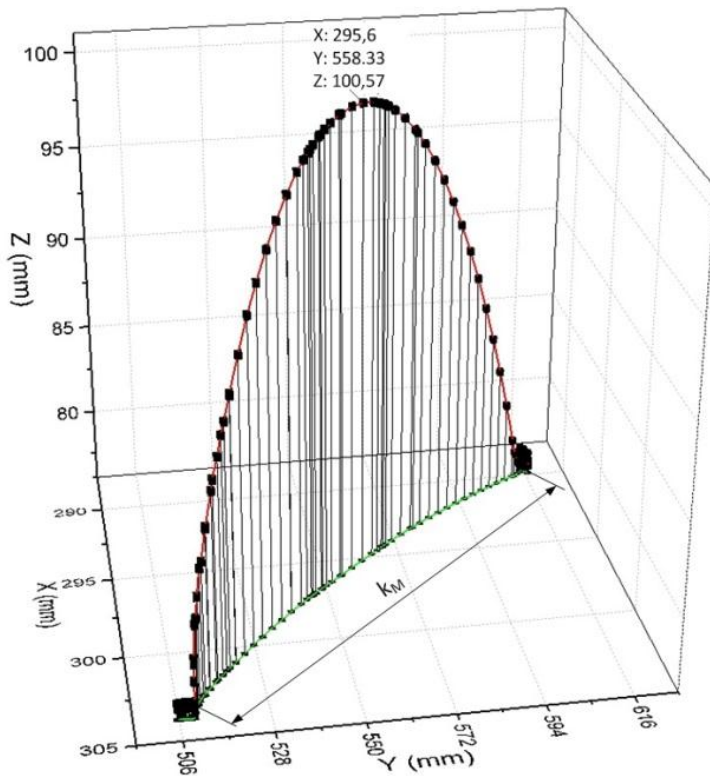

Fig. 10. Path chart of tilting structure (own study)

3. DETERMINATION OF BALANCED POSITION

Balanced position is relative stage of the object body which comes into existence by balancing of forces which determine this condition (Swivel walker, 2016). For this status must be fulfilled condition that all forces and torque forces applied on the object were balanced (Kaňuch, & Kostelný, 2008). Due to the gravitation object has to be stable in all conditions it means balance out gravitation. In this case balanced conditions of the object is taken as an indifferent (even after tilting of the object CoG is still in the same height level and the axis of gravity passes through area of support construction) (Baláž & Sukop, 2005; Hajduk, 2007).

For bipedal structure it is so called double support position, design condition of balance is so that cross point of the gravity axis is near the center of foot supporting area with the base in every phase of movement see picture fig. 11.
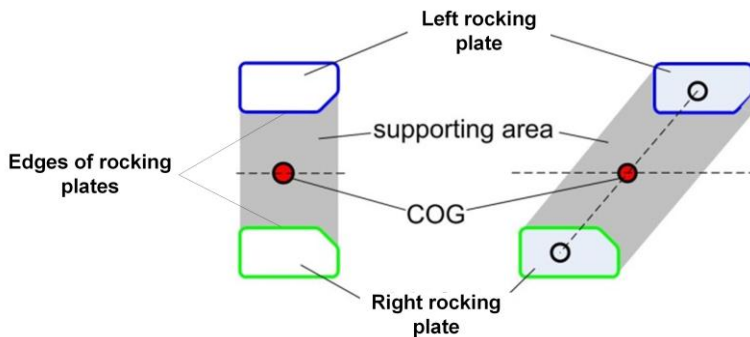
Fig. 11. Double support position (own study)

Important parameter for stability keeping is the distance between the edge of rocking plate and centre of equipment CoG. Gravity axis must not go out of the rocking plate area because system becomes static unstable.

4. CONCLUSIONS

This paper described analyses of humanoid walking – move to forward, proposal of electromotoric module for swivel walker with its structure and located on the base plate. This is an innovative and modern design of Swivel walker. Main advantage is using swivel walker with electromotoric module for people with higher degree of disability. User can choose from two variants: classic swivel walker or swivel walker with electromotoric module.

ACKNOWLEDGEMENT

REFERENCES

Baláž, V., & Sukop, M. (2005). Multiagentnije sistemy. In: *Automation: problems, ideas, decisions: Materiálová medzinárodná náučno-technická konferencia* (pp. 124-127). Sevastopol: SevNTU.

Butler, P. B., Farmer, I. R., Poiner, R., & Patrick, J. H. (1982). Use of the Orlau swivel walker for the severely handicapped patient. *Physiotherapy*, *68*(10), 324-326.

May, C. S., Broadhurst, M. J., & Major, R. E. (2004). Comparison of rocking edge spacing for two common designs of swivel walkers. *Prosthetics and orthotics international*, *28*(1), 75-80.

Stallard, J., Lomas, B., Woollam, P., Farmer, I. R., Jones, N., Poiner, R., & Miller, K. (2003). New technical advances in swivel walkers. *Prosthetics and Orthotics International, 27*(2), 132-138. doi:10.1080/03093640308726669

Čirip, M., & Hajduk, M. (2010). Návrh stabilizácie a matematických modelov kráčania humanoidných robotov. *písomná práca k dizertačnej skúške*. Košice.

Hajduk, M. (2007). Present status and evolution trend of service and humanoid robotics. In *Service and Humanoid Robotics*. Košice.

Hajduk, M., Baláž, V., & Sukop, M. (2005). Sorting workstation with colour sensors. In *Proceedings of SAMI'2005 - 3rd Slovakian-Hungarian Joint Symposium on Applied Machine Intelligence* (pp. 353-357). Herľany, Slovakia.

Knoflíček, R., & Haltmar, M. (2000). Konštrukcia mobilných robotov (1-5). *MM-Priemyslové spektrum, 2-6*.

Kaňuch, J. (2007). Applications of brushless DC motors. In: *LVEM 2007 – Low Voltage Electrical Machines*. Brno: University of Technology.

Kaňuch, J., & Kostelný, M. (2008). Inverse synchronous motor with permanent magnets. In: ISEM 2008 (pp. 137-145). Prague: Czech Technical University.

Świć, A., Wołos, D., Zubrzycki, D., Opielak, M., Gola, A., & Taranenko V. (2014). Accuracy Control in the Machining of Low Rigidyty Shafts. *Applied Mechanics and Materials*, *613*, 357-367. doi: 10.4028/www.scientific.net/AMM.613.357

Świc, A., & Taranenko, W. (2012). Adaptive Control of Machining Accuracy of axial-symmetrical low-rigidity parts in elastic-deformable state. *Eksploatacja I Niezawodnosc-Maintenance and Reliability,14*(3), 215-221.

Swivel walker. (2016). Retrieved from http://www.prowalk.de/kinder-mobil-machen/swivel-walker.html

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WEB ANALYTICS COMBINED WITH EYE TRACKING FOR SUCCESSFUL USER EXPERIENCE DESIGN: A CASE STUDY

Abstract

The authors propose a new approach for the mobile user experience design process by means of web analytics and eye-tracking. The proposed method was applied to design the LUT mobile website. In the method, to create the mobile website design, data of various users and their behaviour were gathered and analysed using the web analytics tool. Next, based on the findings from web analytics, the mobile prototype for the website was created and validated in eye-tracking usability testing. The analysis of participants' behaviour during eye-tracking sessions allowed improvements of the prototype.

1. INTRODUCTION

The popularity of mobile devices provides new opportunities for website owners to reach users regardless of time or their location. However, creating a miniaturised version of the regular website is not a solution for mobile users. Mobile devices introduce new limitations, such as small screen sizes, wireless bandwidth or new interaction mechanisms based on gestures. The platform, user context, business context and technologies (Ballard, 2007) involved may differ as well. Therefore, creating a positive mobile user experience is an increasingly important and demanding task for website and application designers.

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The term *user experience* (UX) is defined as "a person's perceptions and responses that result from the use or anticipated use of a product, system or service" (ISO 9241-210, 2010). What is important, UX results not only from the system presentation, functionality, performance, interactive behaviour or assistive capabilities. It is also effected by the user's former experiences, skills, preferences and even emotions.

Web analytics is the measurement and analysis of web site usage, whereby the complex interactions between web site user and web site can be better understood and optimized (Phippen et al., 2004). Therefore web analytics can lead to a significant improvement of the website user's experience.

Eye-tracking is the process of measuring either the point of gaze or the motion of an eye. Eye-tracking can provide precise information about users' interactions with any interface by determining either where the eye is focused or the motion of the eye on the interface.

User experience design (UXD) is a discipline aimed to fulfil the users' needs and motives via product usage (Michailidou, Haid & Lindemann, 2015) by influencing their perceptions and behaviour (Unger & Chandler, 2012). The UXD process consists of five key phases: Strategy, Research, Analysis, Design and Production. At each of them designers use various sets of techniques to achieve a positive UX.

The paper presents an approach (as a set of techniques) ensuring a positive user experience for a mobile web design based on web analytics and eye-tracking techniques. The advantages of the method are a short research phase thanks to web analytics data collection and effective usability evaluation through the eye-tracking study used during the design phase.

The paper is organised as follows: Section 2, *State of the art*, presents the UX methods and techniques used to develop and evaluate mobile websites. A detailed description of the proposed approach for UXD is provided in Section 3, *A proposed method*. Section 4 presents a case study based on the proposed method for developing a mobile website for the Lublin University of Technology (LUT). The work discussed is summarised in the last section, *Conclusions*.

2. STATE OF THE ART

With the growing popularity of mobile devices, innovating methods and tools for mobile user experience (UX) research have been developed. The review focuses on UX research and evaluation methods like web analytics and user-based evaluation applied for mobile website design with an emphasis on educational institutions.

2.1. Web analytics in UXD

Beasley states that in UXD web analytics adds to or complements other UX methods. The most advised use of web analytics in UXD is to verify how well the findings from traditional methods on small group of users replicate on large populations of users, or to test the effectiveness of design changes (Beasley, 2013).

In his work, Bohyun Kim (2013) presents several studies in which university libraries surveyed thousands of patrons (with response rate of about 40%) to gather information about their attitude and expectations from a mobile library website. Moreover, some universities decided to form a focus group to better understand users' needs and carefully investigate the desirable features of a mobile library website. A contrary example of substituting paper-based and online surveys with web analytics to track behaviours of library website users and recognise their motivation is presented in (Fang & Crawford, 2008). The authors emphasise that web analytics in combination with the library system transaction logs helped to measure usability and redesign the existing website interface in a user-centred manner. Analogously, Loftus (Loftus, 2012) describes web analytics as a free and low-cost tool used for gathering data for a library website in an iterative design process.

A set of web analytics metrics useful for quick identification of usability problems with an e-commerce site is proposed by Hasan et al. (Hasan, Morris & Probets, 2009). Although such metrics can provide an overview of a site's usability or indicate a potential area of usability problems, to get more understanding of the issue, some other technique of usability evaluation is needed.

Another approach is proposed by Djamasbi et al. (Djamasbi et al., 2014). In their work, web analytics is used to measure the UX of an actual e-commerce website before and after it was optimised for mobile devices to verify the impact of the changes.

2.2. Mobile user experience evaluation

Diaz et al. in their works present the design process of a mobile educational website. Within the process, heuristic evaluation based on the W3C norms for mobile devices (Diaz, Harari & Amadeo, 2008b) as well as usability testing with users (Diaz, Harari & Amadeo, 2008a) were applied. As the authors declare, both methods were effective in identifying usability problems and gathering recommendations for a final redesign of the mobile interface.

An interesting study of the mobile websites of large research universities and their libraries is presented in (Aldrich, 2010). Based on expert evaluation of the mobile websites and apps of several universities and libraries, the author determined a set of features to provide more student-centric services on their mobile websites. Similarly, Liu & Briggs (2015) evaluated the current state

of mobile websites among university libraries as well as their best practices through website inspection and survey questionnaires. Based on the results from Aldrich, Liu and Briggs' findings, the study of the level of adoption of mobile access to the academic libraries in the best universities, as well as the quality of services using expert evaluation, is presented in a paper by Torres-Pérez et al. (2016).

The heuristic evaluation of the mobile website of an Asian university is presented in Fung et al. (2016). The authors used Nielsen's ten usability heuristics to identify usability issues and the adequate improvements applied.

The eye-tracking technique, applied to UX evaluation, provides evidence of what attracts users' attention and what their preferences are of website content according to demographics (Djamasbi, Siegel & Tullis, 2010), how website complexity affects user's cognitive load (Wang et al., 2014) or how placement of web objects on different types of websites influences users (Roth et al., 2013). Eye-tracking applied to mobile interface evaluation can also reveal the preferred users' interaction strategy or interaction issues like improper sizing of a touchable element or inadequate gesture choice (Borys & Milosz, 2015).

The general assessment of the co-evolution of mobile UX methods and tools by considering requirements is presented in a paper by Nakhimovsky et al. (Nakhimovsky, Eckles & Riegelsberger, 2009). The comparative study of usability methods, including evaluation method for mobile applications, can be found in (Zaid, Jamaludin & Wafaa, 2012). An overview of user-based evaluation of mobile interfaces (Alshehri & Freeman, 2012; Coursaris & Kim, 2011), as well as heuristic evaluation (De Lima Salgado & Freire, 2014), is presented in these recent works.

3. A PROPOSED APPROACH

2.1. Methodology

The proposed approach for mobile website design follows the UXD process (Fig. 1). The strategy as well as production phases are beyond the scope of this work and will not be explained. The emphasis will be placed on the research, analysis and design phases.

The present approach is recommended for the development of a mobile website from an already accessible regular website. Additionally, web analytics data should be available a priori, therefore earlier installation of a web analytics tool is required.

Fig. 1. A proposed approach for mobile website design process (own study)

In the present approach, to gather information about users, web analytics is utilised. An advanced web analytics tool allows not only for acquisition of all the website users' data, it also provides options to choose specific segments of users (i.e. smartphones and tablet users) to analysis. Having once acquired the data, their analysis can be performed to better understand mobile users, their behaviours and needs. The results analysis provides mobile users' profiles and use cases (a form of system functional requirements). This allows to create an information structure and design an interactions mechanism for a mobile website.

When the information structure as well as interactions mechanism for a mobile website are recognised, the design phase could be started. This phase begins with the development of an interactive prototype. The more elements are implemented into the prototype, the more interactions can later be evaluated and adjusted. However, for a large website it is impossible to transfer all content or implement all functionality into the prototype. Therefore, the main attention should be placed into screens related to the use cases identified during the analysis.

Having the prototype, a user-based evaluation in the form of user testing can be conducted. To uncover more information about user behaviour, the user testing session should be supplemented with eye-tracking technology. The variety of eye-tracking devices allows for testing not only in laboratory environment, but also in users' natural environments or quasi-real conditions. The usage of the eye-tracking technique during user testing allows to integrate traditional usability metrics (related to user satisfaction, efficiency and effectiveness) with eye-tracking metrics (representing user visual attention, cognitive cost or load).

The analysis of user testing should not only identify usability issues, but also provide some insights for prototype improvement or final website design implementation. If a large number of significant usability problems are found, the user testing might be repeated. When the design phase is finished, the mobile website design can be finally implemented.

3.2. Advantages and shortcomings

The most important advantage of the present approach is the application of web analytics in order to gather information about users and then to analyse them. In particular, web analytics provides access to users' demographics, location and language settings, their technology, including device and screen information, operating system, browser, networks, activities (clicks, site searching, form filling), engagement, frequency of visits, and their acquisition channels.

Web analytics is a low-cost and time-effective method, besides installation process it does not require any additional effort. It gives access to a large population and thereby prevents indecorous respondent selection. What is more, web analytics not only provides data about the current state, it reveals the evolution of online trends and user behaviours. Finally, unlike other methods, web analytics provides objective data.

Another strength of the approach is integration of user testing with eye-tracking, which allows to better identify design issues in mobile design, taking into account its limitations. The insights gained about mobile users' visual attention and preferred ways of interaction lead to more effective and efficient interface design.

The major limitation of the method is the need to use an eye-tracking device, which is specialised equipment. However, on the market there can be found many low-cost eye-tracking devices that can be applied to visual-attention tracking.

The other shortcoming is connected with the user testing setup. Significant differences were found between usability tests on mobile phones conducted in laboratory and in a real life situation, including the frequency and severity of usability problems encountered, the users' behaviour, and subjective responses of users (Duh, Tan & Chen, 2006). Moreover, whether the usability testing is conducted on a mobile device or a desktop emulator, can influence testing results such as the mean task completion times and mean fixations per task (Levulis & Harris, 2015). Therefore, those implications should be taken into account during planning user testing experimentation.

4. A CASE STUDY: THE LUT MOBILE WEBSITE

Everyday more than 5 thousand users visit the Lublin University of Technology (LUT) website and about 20% of them use smartphones and tablets. Nevertheless, the LUT website is not responsive or does not have its mobile version to meet the needs of those mobile users.

4.1. Web analytics in work

Firstly, to understand mobile website usage and behaviour patterns, a large set of web analytics data were utilised. Web analytics led to the identification of mobile user groups, their tasks and the context in which they perform them.

In recent years, a significant increase in the use of the Lublin University of Technology website by using smartphones and tablets were noted. For the period from 20.05.2011 to 20.05.2015 the total number of sessions visited by all devices is 6 488 982, including mobile phones 335 689 (5.17%) and tablets 55,445 (0.85%). Detailed information about how mobile device usage changed

over time is presented for the periods of 20.05.2011 to 20.05.2012 and 20.05.2014 to 20.05.2015. In the first period, mobile devices reached 1.05% of total traffic, while in the second there was a significant increase in this value to 10.45%. Similarly, the number of visits from tablets increased, but on a smaller scale – from 0.03% in 2011/2012 to 1.36% in the period 2014/2015.

Recommended resolution for smartphones are: 360x640px, 320x534px, 480x800px and 320x480px. In the case of tablets, these values are: 768x1024px and 1280x800px. Currently, in the case of mobile devices, Google Chrome leads with a value of 50.79% of all visits. In the next position is a native browser of Android devices with a value of 21.55%, third place in the ranking is the browser iOS Safari with a score of 12.07%. Two most popular operating systems on mobile devices are Google Android and Apple iOS. Current data indicate a significant advantage of the operating system of Google – Android has 81.34% of visits from mobile phones, the next position is occupied by Apple's iOS with a value of 8.05%, in the third place is Windows Phone (7.28%). 1.06% of the devices were not recognised by the operating system. The percentage distribution of the operating systems used on tablets are: Google Android (54.73%), Apple iOS (36.88%), Windows (7.86%), and Firefox OS (0.52%).

The most interesting pages for most visitors are: information for candidates (6.85%), time-tables (5.22%), and information from the student career centre (3.51%). The remaining percentage of visits is less than 2%. In the case of mobile devices, time-tables are at the first position with 9.23% of all visits, followed by information addressed to students on the subpage */pl/studenci* with a score of 8.63% (for desktop devices it was only 1.88%), the third place is occupied by subpages for candidates with a score of 8.18%.

In order to broaden the information on the pages visited by users, it was decided to use Google Analytics "*In-Page analytics*", showing the number of clicks for a given area of the page in a given period of time.

Moreover, the Lublin University of Technology webpage has been checked for usability and user experience by using the "*Mobile-Friendly Test*" tool. The analysis shows that the LUT website is unsuitable for use on mobile devices. The main reasons of this assessment are: small font, which makes it difficult to read the text, links to other pages located too close to each other and the lack of settings connected with working for a portable device – for smaller screen sizes, the page is displayed on half of the screen of the mobile device, the remaining area is undeveloped (Fig. 2).

Analysis lead to the conclusion that the main functions of the website are:
1. checking the student time-tables;
2. searching for an internship or job opportunities;
3. obtaining information about the recruitment process and studies profiles;
4. obtaining information about scholarships, grants, exam results and university announcements;
5. searching for LUT employee contact information using the address book.

The group that use the Lublin University of Technology website and for which a profile was developed are: students, candidates, LUT employees, LUT graduates and others (including entities cooperating with the university like media, companies or institutions).
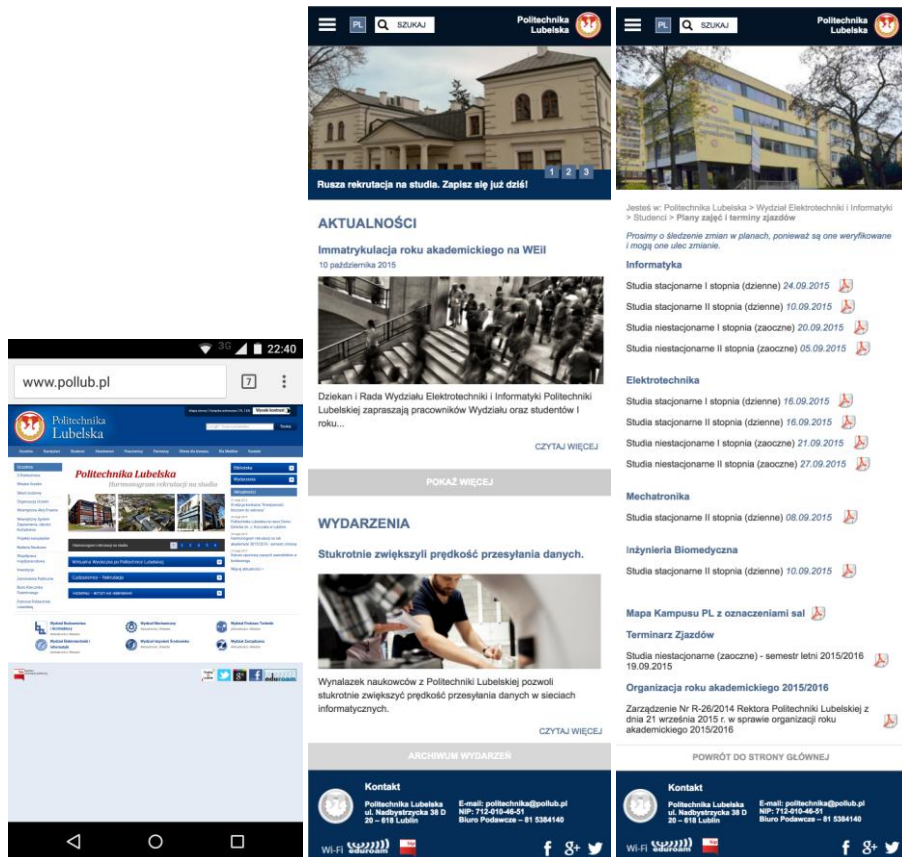
Fig. 2. From the left: homepage of the LUT website displayed in a mobile device, prototype of the LUT mobile website homepage, prototype of the time-tables for the Faculty of Electrical Engineering and Computer Science (own study)

4.2. Prototyping mobile web design

The prototype was created by the prototyping tool Axure RP Pro. The program allows to design a fully interactive mock-up, which simulates normal website interactions.

The design process began with rebuilding the information structure based on previous experience and information gathered from user groups. The real website content was placed into the mobile prototype.

One of the most important components present in the mobile website design is a search engine (Fig. 2). It was deliberately placed at the top of the page, for everyone to quickly find it and search for the desired phrase.

Another component, equally important, but slightly different from the desktop version, is the menu available at the top of the page in the form of a "*hamburger menu*". It consists of 8 categories, 7 of which being drop-down ones.

On the main page, other elements were placed below the slider in the form of articles, directly accessible by clicking on them. In order to facilitate the navigation, the whole article area (titles as well as graphics) link to the article webpage.

The last element on the website is a footer, which was divided into several smaller sections. There is contact information, such as the university's address, contact number and navigation elements to selected university services and social media.

As shown in Figure 2, other webpages also include those main components. Additionally, just before the footer, the return button to the university homepage was placed to allow quick navigation.

4.3. User testing with eye-tracking

To verify and optimise the mobile design, usability testing with eye-tracking was performed. It took place in the Laboratory of Movement Analysis and Interface Ergonomics at the Lublin University of Technology.

A total of 10 participants with 20/20 vision or corrected-to-normal vision took part in this study. Two of the participants had never used the Lublin University of Technology website, while others had used it at least once. Each person was tested in the same way, in the same experimental conditions.

Tobii TX300 Eye Tracker (video-based eye tracker, Tobii Technology AB, Sweden) supplied with a 23" TFT monitor was used to acquire eye-position data at a sampling rate of 300 Hz. Gaze data were recorded from both eyes.

The experiment was created using Tobii Studio 3.2. The mobile website prototype was displayed by the Microsoft IE browser. Participants were seated while working with the prototype. The distance between the screen and the subject was in a range of 50 to 80 cm.

The eye tracker was calibrated using a 9-point built-in calibration procedure at the beginning of each session. Once calibrated, the participants were provided with the experimental instructions on the screen.

The participants were asked to complete the following tasks using the prototype of the mobile website during the session:

A. As a candidate for engineering studies in Computer Science at the Faculty of Electrical Engineering and Computer Science:
    1. find the subjects that should be taken during the matriculation examination to ensure enrolment for the studies,

2. verify how to calculate points in the recruitment procedure,
3. check how to apply for a place in a student dormitory.

B. As a student of the fourth semester in Computer Science at the Faculty of Electrical Engineering and Computer Science:
4. find the timetable and the date of its last update,
5. check the official document on the organisation of the academic year,
6. find an offer for an internship for a programmer for the duration of the winter holidays.

After performing the tasks, participants were asked to complete the questionnaire. It consisted of questions about the participants' satisfaction level in each task, as well as an open question concerning the interface.

In the analysis of the mobile website prototype, the usability metrics and eye-tracking measures were combined. The visualisations of the eye-tracking metrics, such as scanpaths and heat maps, were created by using Tobii Studio 3.2.

The following usability metrics were used in the analysis:
– Task Level Satisfaction (TLS). The user's subjective assessment of how difficult the task was. It measures comfort and acceptability (satisfaction metric). The Likert scale from 1 (very difficult) to 10 (very easy) was used.
– Completion Rates (CR). The completion rate is calculated by assigning binary values: $1 = $ Task success and $0 = $ Task failure (effectiveness metric).
– Task Time (TT). Total task duration measures of efficiency and productivity (efficiency metric).
– Error Rate (ER). The number of any unintended actions, mistakes or omissions all users make while attempting a task (effectiveness metric).
– Number of Interactions (NoI). The number of any interactions made by the user to complete a task (efficiency metric).
– Scrolling Rate (SR). Binary value representing if the user did scrolling interactions to complete a task (efficiency metric).
– Page Views (PV). Total number of user views of a webpage to complete a task (efficiency metric).

The following eye-tracking metrics were used in the analysis:
– Number of Fixations (NoF). The number of fixations, assumed to be negatively correlated with search efficiency.
– Mean Fixation Duration (MFD). Fixation duration indicates the workload of a task. Longer fixations reveal increase in cognitive processing loads.
– Time to First Fixation (TFF). The time to first fixation indicates the amount of time that it takes a user to look at a specific AOI. In this case the "hamburger menu" was selected as the area of interest.

The calculated usability metrics for user testing are presented in Table 1. TLS, TT, NoI and PV are calculated as average values among all participants, ER is presented as a sum of errors all participants made, CR and SR are presented as the percentage of users who completed a task or used the scroll during the process. The calculated eye-tracking metrics as average value among all participants are presented in Table 2.

As presented in Table 1, all participants completed the tasks in less than 1.5 minutes each. It can be noticed that TSL is influenced by NoI performed and correlated with its number of errors performed (more errors cause more user interactions). Those additional interactions are caused by menu arrangements (created information structure). The information structure depth assessed as very satisfied by the participants was 3, which is reflected in PV and NoI.

Tab. 1. Usability metrics (own study)

	TLS	CR	TT	ER	NoI	SR	PV
Candidate							
Task 1	6.9	100%	94s	18	17.2	100%	3.5
Task 2	8	100%	22.86s	0	6,4	100%	3
Task 3	6.7	100%	73,9s	13	12.6	100%	3.3
Student							
Task 4	9	100%	39.2s	1	7.2	40%	3
Task 5	8	100%	59s	1	10	100%	3.5
Task 6	6.9	100%	61s	10	14.6	100%	4

Tab. 2. Eye-tracking metrics (own study)

	NoF	MFD	TFF
Candidate			
Task 1	235.8	0.29	20s
Task 2	58.8	0.34	7.3s
Task 3	200	0.30	16.5s
Student			
Task 4	112	0.31s	4.5s
Task 5	153	0.34s	4.6
Task 6	199	0.30s	3.4

The large NoF as well as long TFF presented in Table 2 for Task 1 (candidate role) can be explained by the first interaction of participants with the interface. Therefore, they spent an adequate amount of time to explore freely all the interface elements. This is also the reason that in this task the cognitive load expressed in MFD is the smallest among all the values in the study.

The navigation path to information searched in Task 2 and Task 4 is well arranged, as evidenced by NoF (small NoF). However, the placement of information for Tasks 3 and 6 should be redesigned, because in those tasks participants revealed ineffective search actions (large NoF).

The scanpath (a sequence of fixations) can indicate the efficiency of the arrangement of elements in the user interface. As presented on Figure 3, for the first few sections of their interaction with the homepage participants explored the top menu ("hamburger menu") with its options. When they viewed other webpages, like time-tables or studies information webpages, their gaze was more distributed on the webpage content.
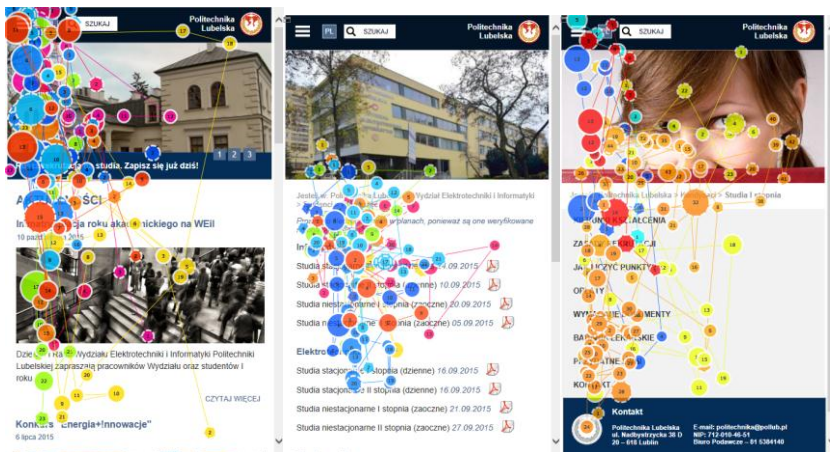

Fig. 3. Scanpaths for the homepage, the timetables webpage and the information about Engineering studies page, with duration limited to the first 10s (own study)
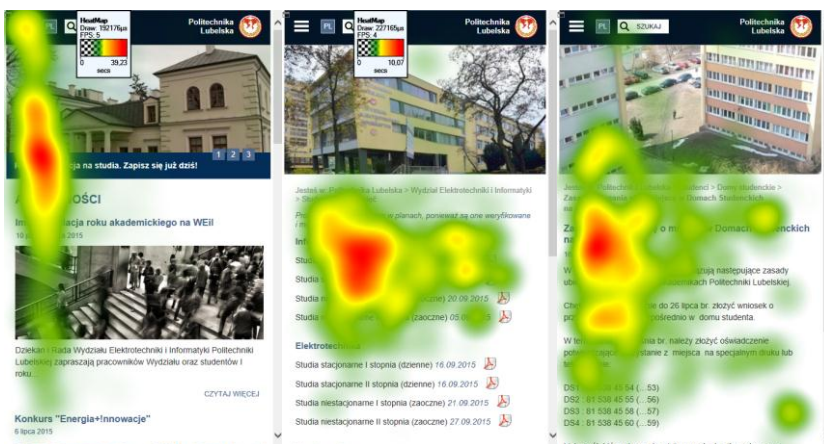

Fig. 4. Heat map for homepage, time-tables webpage and dormitory placement page (own study)

Heat maps show the general distribution of fixations. Such maps were generated for the homepage, time-tables webpage and dormitory placements page (Fig. 3). Heat maps for the latter two webpages prove that participants omit the image presented below the menu and read the content presented below. This demonstrates that the image has only a decorative purpose: it does not provide any information to the users and force them to scroll to reach the full content, therefore it should be removed.

4.4. Mobile website redesign

Finally, the analysis of usability metrics and eye-tracking measures enabled the prototype improvement – the final version of the LUT mobile website design.

These changes are related mainly to the structure of the menu – the location of the sub-category, reorganising the content placed on the webpages, or redundant links to specific pages.

Menu improvements involved removing submenu items that did not provide clear information (such as: "*Must have for future student*" or "*Information about the studies*" from the submenu *Candidates*). These items described general information about studying in the form of PDF files, updated occasionally, which interrupt the user's natural flow of on the website.

Such redundancy links lead to more effective navigation paths for the most frequent tasks. For example a new menu item in the *Candidates* submenu called *Dormitory* was added, although it was already present in the *Students* submenu, because a majority of respondents searched for information on dormitories there. The submenu *Students* has been moved to the top of the menu to make the *Schedules* webpage faster accessible.

The path followed by participants during their search for jobs on vacation often affects the "IT industry" links in the Careers Office, because – as suggested by the current desktop version – there may be information about work or internships in the IT industry.

Moreover, the decorative image placed below the top menu on webpages other than the homepage was removed. Users did not pay attention to the image, but it caused the page-scrolling action aimed at getting to the main content.

5. CONCLUSIONS

The proposed approach for mobile website design follows the UXD process, however the main focus is placed on the research, analysis and design phases. The approach is recommended for development of mobile websites from already accessible regular websites, and installed web analytics for data acquisition.

The most important advantage of the present approach is the application of web analytics to gather and analyse information about users, because web analytics is a low-cost and time-effective method. The other strength of the approach is integration of user testing with eye-tracking, which allows to better identify design issues in mobile design. The limitations of the method are the need of using an eye-tracking device, which can be costly depending on equipment/model/version/... selection, and some differences in user performance between different testing setups, especially in laboratory environment.

However, as was hopefully demonstrated in this case study, the approach allows for efficient and effective interface designing for a valuable mobile user experience.

REFERENCES

Aldrich, A. W. (2010). Universities and libraries move to the mobile web. *Educause Quarterly*, *33*(2), 5.

Alshehri, F., & Freeman, M. (2012). Methods of usability evaluations of mobile devices. In J. W. Lamp (Ed.), *23rd Australasian Conference on Information Systems* (pp. 1-10). Geelong: Deakin University.

Ballard, B. (2007). *Designing the mobile user experience*. John Wiley & Sons.

Beasley, M. (2013). *Practical web analytics for user experience: How analytics can help you understand your users*. Morgan Kaufmann.

Kim, B. (2013). The Present and Future of the Library Mobile Experience. *Library Technology Reports*, *49*(6), 15-28.

Borys, M., & Milosz, M. (2015). Mobile application usability testing in quasi-real conditions. In *Proceedings – 2015 8th International Conference on Human System Interaction, HSI 2015* (pp. 381-387). Institute of Electrical and Electronics Engineers Inc.

Coursaris, C. K., & Kim, D. J. (2011). A Meta-Analytical Review of Empirical Mobile Usability Studies. *Journal of Usability Studies*, *6*(3), 117-171. Retrieved from http://dl.acm.org/ citation.cfm?id=2007456.2007459

Salgado, A. D., & Freire, A. P. (2014). Heuristic Evaluation of Mobile Usability: A Mapping Study. *Human-Computer Interaction: Applications and Services, Pt Iii, 8512*, 178-188. doi: 10.1007/978-3-319-07227-2_18

Diaz, F. J., Harari, B. S. I., & Amadeo, B. S. P. (2008). Evaluating the Usability of the Mobile Interface of an Educational Website. *Innovative Techniques in Instruction Technology, E-learning, E-assessment and Education*, 47-52. doi:10.1007/978-1-4020-8739-4_9

Diaz, J., Harari, I., & Amadeo, P. (2008). WW3C mobile web best practices evaluation of an educational website. *Proceedings of the International Conference on Information Technology Interfaces*, *ITI*, 421-426. doi:10.1109/iti.2008.4588447

Djamasbi, S., McAuliffe, D., Gomez, W., Kardzhaliyski, G., Liu, W., & Oglesby, F. (2014). Designing for Success: Creating Business Value with Mobile User Experience (UX). In F. F.-H. Nah (Ed.), *HCI in Business: First International Conference, HCIB 2014, Held as Part of HCI International 2014, Heraklion, Crete, Greece, June 22-27, 2014. Proceedings* (pp. 299-306). Springer. doi:10.1007/978-3-319-07293-7_29

Djamasbi, S., Siegel, M., & Tullis, T. (2010). Generation Y, web design, and eye tracking. *International Journal of Human-Computer Studies*, *68*(5), 307-323.

Duh, H. B.-L., Tan, G. C. B., & Chen, V. H. (2006). Usability evaluation for mobile device: A comparson of laboratory and field tests. *Proceedings of the 8th Conference on Human-Computer Interaction with Mobile Devices and Services – MobileHCI '06* (pp. 181-186). ACM. doi: 10.1145/1152215.1152254

Fang, W., & Crawford, M. E. (2008). Measuring Law Library Catalog Web Site Usability: A Web Analytic Approach. *Journal of Web Librarianship*, *2*(2-3), 287-306.

Fung, R. H. Y., Chiu, D. K. W., Ko, E. H. T., Ho, K. K. W., & Lo, P. (2016). Heuristic Usability Evaluation of University of Hong Kong Libraries' Mobile Website. *Journal of Academic Librarianship, 42*(5), 581-594. doi:10.1016/j.acalib.2016.06.004

Hasan, L., Morris, A., & Probets, S. (2009). Using Google Analytics to evaluate the usability of e-commerce sites. In *International Conference on Human Centered Design* (pp. 697-706). Springer. doi: 10.1007/978-3-642-02806-9_81

ISO 9241-210. (2010). Ergonomics of human-system interaction – Part 210: Human-centred design for interactive systems, 1-21.

Levulis, S. J., & Harris, D. J. (2015). Are All Tests Equal? A Comparison of Emulator and Device Testing for Mobile Usability Evaluation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 59, No. 1, pp. 976-980). SAGE Publications.

Liu, Y. Q., & Briggs, S. (2015). A library in the palm of your hand: mobile services in top 100 university libraries. *Information Technology and Libraries (Online)*, *34*(2), 133.

Loftus, W. (2012). Demonstrating Success: Web Analytics and Continuous Improvement. *Journal of Web Librarianship*, *6*(1), 45-55. doi: 10.1080/19322909.2012.651416

Michailidou, I., Haid, C., & Lindemann, U. (2015, August). How to Evaluate Use Scenarios and Stories. In *International Conference of Design, User Experience, and Usability* (pp. 609-620). Springer.

Nakhimovsky, Y., Eckles, D., & Riegelsberger, J. (2009). Mobile user experience research: challenges, methods & tools. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems* (pp. 4795-4798). ACM. doi: 10.1145/1520340.1520743

Phippen, A., Sheppard, L., Furnell, S. (2004). A practical evaluation of Web analytics. *Internet Research*, *14*(4), 284-293. doi: 10.1108/10662240410555306

Roth, S. P., Tuch, A. N., Mekler, E. D., Bargas-Avila, J. A., & Opwis, K. (2013). Location matters, especially for non-salient features-An eye-tracking study on the effects of web object placement on different types of websites. *International Journal of Human-Computer Studies, 71*(3), 228-235. doi:10.1016/j.ijhcs.2012.09.001

Torres-Perez, P., Mendez-Rodriguez, E., & Orduna-Malea, E. (2016). Mobile Web Adoption in Top Ranked University Libraries: A Preliminary Study. *Journal of Academic Librarianship, 42*(4), 329-339. doi:10.1016/j.acalib.2016.05.011

Unger, R., & Chandler, C. (2012). *A Project Guide to UX Design: For user experience designers in the field or in the making*. New Riders.

Wang, Q. Z., Yang, S., Liu, M. L., Cao, Z. K., & Ma, Q. G. (2014). An eye-tracking study of website complexity from cognitive load perspective. *Decision Support Systems, 62*, 1-10. doi:10.1016/j.dss.2014.02.007

Zaid, B., Jamaludin, R., & Wafaa, B. (2012). A Comparative Study of Usability Methods for Mobile Applications. *International Journal of Scientific & Engineering Research*, *3*(8), 1-4.