A Computational Framework for a Bio-inspired Mechanism of Vernier Hyperacuity

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Abstract: In this paper, we present a bio-inspired computational framework for the hypothetical cooperation of the ocular drift and a place coding neural circuitry. The proposed bio-inspired mechanism can provide an explanation for the ability of primate vernier hyperacuity. Our starting point is a spatiotemporal model of the primate retinal P and M ganglion cells. First we show that in the central retina, the drift-induced movement moves the stimuli of preferred spatial frequency with a velocity that is optimal for P cells and almost "invisible" for the movement-sensitive M cells. Secondly, based on a presumed analogy between the owl's auditory system and a primate visual system we present a theory that visual hyperacuity can be originated to the detection of time delays between neural firing patterns. Third, we propose a possible neural model for the place coding circuitry. Our new theory may serve suggestions for further research.

Keywords: ocular drift; place coding circuitry; hyperacuity; computational model

1 Introduction

Vernier acuity is a measure of the smallest offset between two line segments that can be discriminated. Hyperacuity is the ability of the eye to resolve an offset with a resolution better than that imposed by the Nyquist limit of the photoreceptor mosaic. Humans can resolve details with an accuracy of better than one fifth of the size of the most sensitive photoreceptor. The explanation for this remarkable ability has been under debate from its discovery.

At present, a wide range of computational models exists for visual hyperacuity and its perceptual learning mechanism. Without the aim of completeness, we survey the recent relevant studies. One of these states that saccadic eye movements may improve the resolution of the eye. During fixation, the eyes "sample" a scene through microsaccades. These "sampled" images can provide the human brain enough information to resolve hyperacuity tasks [35]. Another theory

assumes that the spatial fluctuations of retinal sampling and the temporal fluctuations caused by eye-tremors can induce noise-enhanced processing effects, providing the hyperacuity phenomenon [71]. Furthermore, a model in [70] states that hyperacuity and its dependence on stimulus length can be realized by the integration of information from more than a single neuron.

In this work we present a bio-inspired theory about the perceptual mechanism of primate vernier hyperacuity. We assume that the small spatial offset in vernier acuity tasks is converted into an appropriate time offset between the firing patterns of the corresponding neurons. We show that an involuntary eye-movement – the ocular drift – may be responsible for this conversion. The proposed mechanism and the underlying neural circuitry makes it possible to convert unresolvable spatial offsets into resolvable time differences. As far as we know, there are no similar theories that would find a functional connection between ocular drift and visual hyperacuity.

The paper is structured as follows. In Section 2 we give a brief overview of our model retina. The model is comprehensible without a detailed knowledge of retinal functionality. This section ensures only the reproducibility of our numerical simulations. Sections 3 and 4 present an overview of the properties of ocular drift and visual hyperacuity. In Section 5 we introduce our bio-inspired computational model and show our simulation results. Finally the occurring questions are discussed in Section 6.

2 Methods

In this study we use a computational model of the light-adapted primate retina regarding to the four main type of retinal ganglion cells (the ON and OFF subtypes of P and M ganglion cells). The model aims to establish a comprehensive accumulation and representation of knowledge about many aspects of the primate retina, including details that are directly reported in the literature, as well as those that are carefully inferred from studies in other species. The model converts the retinal morphology into a transfer function representation. Here we give a brief description of our model retina.

1) Our starting point was the analytical approximation of cone and total ganglion cell density along the surface of the entire human retina. Both approximations are based on the measured dataset of Curcio et al. [12, 13]. Results were compared with others [69, 25, 2, 45]. Regarding to ganglion cells, the method of Drasdo et al. [19] was used to handle the effect of lateral displacement. The resulted foveal ganglion-cell-to-cone ratio was compared with measured values [13, 54, 55, 19, 42, 50, 60, 63, 29, 1].

2) We calculated the ratio of P, M and K cells[1]. The formulas are based on the estimations in [50, 15, 3] and have been validated by the cumulative number and ratio of the RGC types [26, 14, 15, 41].

3) The ratio of ON and OFF cells to the total P and M cell population were also estimated corresponding to the observations in the literature [15, 16, 1, 33, 19].

4) From the density of the different cell types, the spacing of the receptive field mosaic was determined in function with eccentricity. Using the measured angle of RF[2] center's overlap [27, 28, 8, 65], the radii of the RF centers can also be estimated. Given the radius of each cell's RF center and considering the experimentally measured center/surround ratio [11], we computed the full extent of the receptive fields.

5) Using the well-known Difference-Of-Gaussians modeling approach [47], the spatial sensitivity functions of P and M cells can also be computed [64, 11, 22].

6) Regarding the temporal sensitivity functions of these ganglion cells, we used well-known measurements and approximations. In [32, 6, 7] the authors give a transfer function representation for P and M cell RF center and surround. The measurements were made on Macaca fascicularis, using drifting sinusoidal gratings at 1123 td (P cells) and 1180 td (M cells) retinal luminance levels.

7) The general form of estimating RGC response is as follows [38, 31].

$$R = \left(S_{rfc}(v)T_{rfc}(j\omega) - S_{rfs}(v)T_{rfs}(j\omega)\right)LC$$

Where R is the response *[imps/sec]* of a ganglion cell, S_{rfc} and S_{rfs} are the spatial sensitivities, T_{rfc} and T_{rfs} are the temporal sensitivities of the RF center and surround respectively. L and C are stimulus properties: the mean retinal illuminance and the Michelson contrast. Spatial and temporal frequencies are denoted by v and ω.

Figure 1 shows the spatial sensitivity functions of two types of retinal ganglion cells (OFF-P and OFF-M), calculated from our model. The boundaries of the colored domains represent the spatial frequencies corresponding to the *-3dB* and *-6dB* values of the spatial sensitivity functions. The density of both P and M cells rapidly decreases toward the periphery, with the result that the size of the receptive fields increases and thus the preferred spatial frequencies decreases significantly. The curves in Figure 1 well correlate with the findings that human high-contrast acuity is about *60 cycles/degree* (P cells at zero eccentricity) [19], while low contrast sensitivity has a maximum around *3 cycles/degree* at the fovea

[1] P: Parvocellular (midget). M: Magnocellular (parasol). K: Koniocellular (bistratified). RGC: Retinal Ganglion Cell

[2] RF: Receptive Field

(M cells at zero eccentricity) and decreases to about *0.2-0.3 cycles/degree* at the far periphery [4].

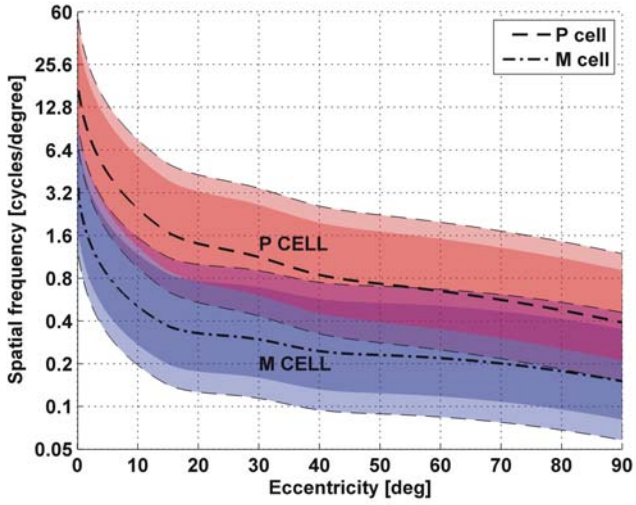

Figure 1

Spatial sensitivity function of two RGC types (OFF-P and OFF-M) in function with eccentricity. The boundaries of the red and yellow domains represent the spatial frequencies corresponding to the *-3dB* and *-6dB* values of the spatial sensitivity.

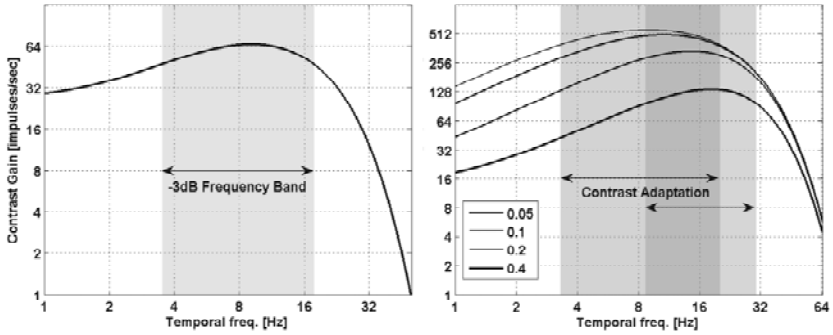

Figure 2

Left: A typical linear filter model to P cell response in the frequency domain. *Right:* A typical linear filter model to M cell response at different contrast levels (0.05-0.4). The contrast adaptation modifies the dynamics of the M cells. With increasing local contrast, the M cell peak temporal frequency shifts from *~9 Hz* to *~17 Hz.* The filled domain represents the preferred (-3dB) frequency band of the cells. Stimuli: drifting sinusoidal grating, spatial frequency was optimal for the cells. Subject: Macaca fascicularis. Retinal luminance level: 1123 td (left) and 1180 td (right).

Figure 2 shows the typical temporal sensitivity functions of P and M cells for achromatic stimuli at photopic light levels. In the primate retina M cells show contrast gain control [21, 53, 31, 6], while P cells do not [38, 53, 32]. The contrast gain control modifies the dynamics of the M cells. With increasing local contrast, the M cell peak temporal frequency shifts from *~9 Hz* to *~17 Hz* [17, 5, 38, 7].

Given the model retina, we can calculate the effect of involuntary eye movements on the retinal cells. In the following section we give a brief description of the ocular drift and we analyze the effect of drift-induced stimulus movement on the P and M ganglion cells.

3 Ocular Drift

Drifts are slow involuntary motions of the eye occurring between microsaccades, simultaneously with tremor. During drifts, the image of the object being fixated can move across several photoreceptors [46] (Figure 3). Initially, drifts seemed to be random motions of the eye generated by the instability of the oculomotor system [18, 10], but later were found to have a compensatory role in maintaining accurate visual fixation in the absence of microsaccades, or at times when compensation by microsaccades was relatively poor [57].

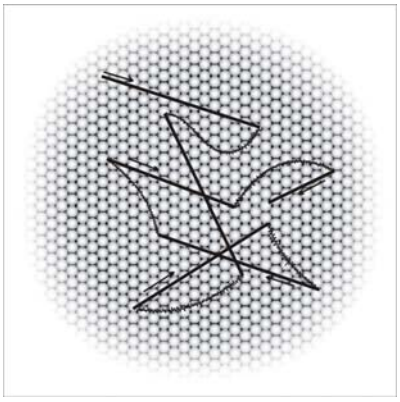

Figure 3
Involuntary eye-movements: Slow drifts (curved lines) and tremor (superimposed on drifts). Drift periods are interrupted by microsaccades, the fast jerk-like eye-movements.

The mean amplitude of the ocular drifts is between *1.2* and *6 arcmin*, while the average velocity ranges between *6 and 12 arcmin/sec* [39]. It is worth noting that – like a "rule" – the drift reaches its almost maximal velocity (close to *30 arcmin/sec*), several times per second [68].

Using our retina model, we can calculate the effect of the ocular drift on P and M ganglion cell response. The motion of the eye evidently induces a motion of the stimulus on the retinal surface. An achromatic contrast stimulus – traveling on the retina with the drift velocity – represents a dynamic input for a retinal cell. Without loss of generality, assuming a sinusoidal (spatial) contrast grid, a ganglion cell receptive field receives a time-varying sinusoidal contrast input. The temporal frequency of the contrast input can be calculated by multiplying the grid spatial frequency with the drift velocity.

We compared the ganglion cells' preferred temporal frequency domain with the "drift-induced" temporal frequency. In Figure 4 the thick black lines represent the cell's preferred spatial frequency multiplied by the average drift velocity. The narrow domains show the -3dB spatial frequency band multiplied by the average drift velocity, while the wider domains represent the same spatial frequency band multiplied by the upper and lower limits of drift velocity. The gray domains show the preferred temporal frequency bands of M and P cells respectively (as shown in Figure 2).

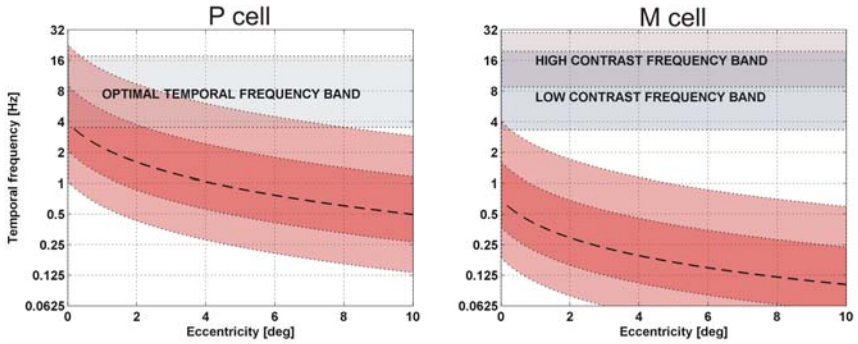

Figure 4
Temporal frequencies induced by ocular drift for M *(left)* and P *(right)* cells. The gray domain shows the cells' preferred frequency bands as shown in Figure 2.

In the central retina, M cells have much larger receptive fields compared to P cells. This property makes the M cells sensitive to lower spatial frequencies (*~3 cycles/degree*). In Figure 4 it clearly seems that the relatively slow ocular drift cannot move the stimuli of these low spatial frequencies fast enough to produce temporal frequencies in the cell's preferred frequency domain. In other words, M cells cannot respond vigorously to the drift-induced motions of the preferred stimuli. After all it is that a cell type involved in movement detection would not be "misled" by an involuntary eye movement.

P cells – which have a very small receptive field – are sensitive to high spatial frequencies (up to *60 cycles/degree*). These fine details – moving by the drift velocity – produce temporal frequencies high enough to elicit considerable cell responses. It means that the drift induced motion may be appropriate for producing P cell activity (Figure 4).

The knowledge of the spatial and temporal properties of retinal cells gives us the opportunity to calculate the human visual acuity, but the phenomenon of hyperacuity cannot be explained based on these data. The next section gives a short overview of human visual hyperacuity and the neural basis of the owl's auditory hyperacuity.

4 Hyperacuity

The term "sensory acuity" refers to the ability of the brain to resolve fine details. Visual acuity is the ability to discriminate the finest detail, for example two parallel lines apart. In humans it is limited by the sharpness of the retinal focus and the number of photoreceptors together. The human foveal visual system's acuity is about 1 min of arc (60 cycles/degree).

Hyperacuity is the ability of sensory modalities to detect differences in two or more stimuli well below the sensory resolution. Humans can resolve details with an accuracy of better than one fifth of the size of the most sensitive photoreceptor. Figure 5 shows a typical hyperacuity task.

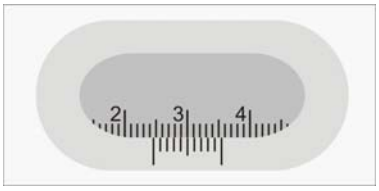

Figure 5
A typical hyperacuity task: reading a sliding caliper

Hyperacuity has been studied for over a hundred years and a wide range of studies provide computational models trying to imitate and explain this phenomenon. However, many aspects of the underlying mechanism are still debated.

The auditory hyperacuity of the barn owl has also been investigated for decades [58, 34]. When localizing its pray, relying solely on acoustic signals, the owl's auditory system can detect shorter delays of time arrivals of sound than the duration of an action potential, which indicates the time arrival. It has been shown that the small time differences of signals from the left and right ears are mapped into a neural place coding circuitry, containing small internal delays and coincidence detector neurons [9] (see Figure 6). The theoretical model – where the place of the neuron with maximum response specifies the corresponding time delay – was first proposed by Jeffres [30], and experimentally verified by [58, 34, 59]. A more detailed model description is presented in [37].

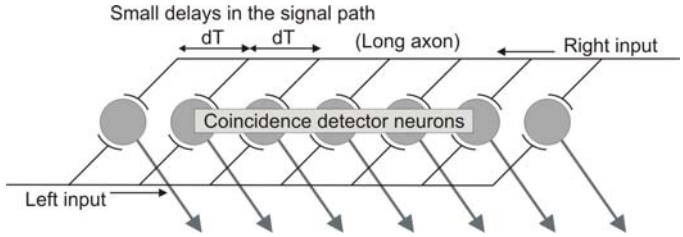

Figure 6

The Jeffres model for encoding small time differences when localizing the source of acoustic signals. The time differences in neural firing patterns are mapped into the "place of the neurons" via coincidence detection of signals arriving from the left and right ears.

5 Results

In this section we introduce an analogy between the owl's localization system and the human vernier hyperacuity. The sound signal (coming from a location) approaches the two sets of receptor cells in the owl's left and right ears (Figure 6). Similarly, the stimulus – moving by the ocular drift on the central retina – approaches the two sets of photoreceptors signed with "A" and "B" in Figure 7 (b).

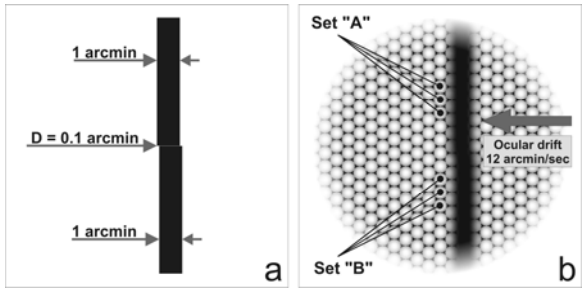

Figure 7

The stimulus - moving by the ocular drift on the central retina - approaches the two sets of photoreceptors signed with "A" and "B". In the foveola, each photoreceptor connects to at least two ganglion cells: an OFF-type and an ON-type P ganglion cell. The firing pattern of "set B" ganglion cells is delayed compared to "set A". The value of the delay is proportional with the angle of the displacement of the stimulus parts and inversely proportional with drift velocity.

In both cases, the time difference in stimulus arrival originates from spatial displacements: the displacement of the two ears of the owl and the displacement of the two line segments (the displacement is signed with *D* in Figure 7 a). The value of time difference can be calculated by dividing the spatial displacement

with the stimulus traveling velocity. In the owl's case it can be as little as some tens of microseconds. In the human visual system (assuming *12 arcmin/sec* mean drift velocity and *D = 0.1* arcmin smallest resolvable spatial offset) the time difference is about 8 ms. The firing pattern of the ganglion cells regarding to the "A" and "B" sets are shown in Figure 7.

In a simulation example, we show that the possible cooperation of ocular drift and a place coding circuitry introduced by [30] is capable of explaining the ability of vernier hyperacuity. We created a computational model of a small part of human foveola, where there are no rods and the great majority (*>95%*) of ganglion cells are P cells. In this small central area every cone is connected to at least two ganglion cells (an off-type and an on-type ganglion cell) and the center of a midget cell receptive field is fed by a single cone [19].

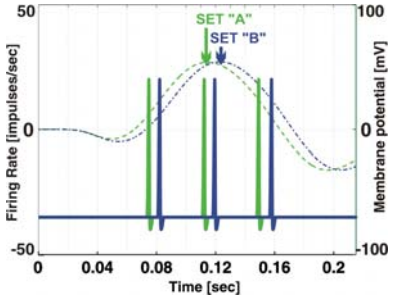

Figure 8

Firing patterns of "set A" and "set B" ganglion cells to the stimulus presented in Figure 7

The stimulus we applied is a classical instance of vernier hyperacuity tasks. The black lines occupy 1 arcmin in width as shown in Figure 7 a. The applied displacements of the two lines are *D = 0.05, 0.1, 0.15 and -0.1 arcmin* respectively. The displacement of *0.1 arcmin* is ten times smaller than the resolving power of the photoreceptor mosaic, and is close to the smallest resolvable difference in hyperacuity tasks. The stimulus is blurred according to the foveal point spread function [19] and moves on the surface of the model retina with 12 arcmin/sec assumed drift velocity (see Figure 7 b).

The firing patterns – evoked by the described stimuli – were used as an input of a coincidence detector circuitry (Figure 9 left side). The delay values were appointed by us to allow *0.05 armin* spatial resolution in space coding. From the viewpoint of this model, it is favorable that P ganglion cells produce a relatively low firing rate, having 7-10 times lower contrast gain compared to M cells [21, 44, 32]. The lower firing rate enables the place coding circuitry to resolve larger time differences without ambiguity.

As shown in Figure 9, the place coding circuit is able to discriminate different degree of displacements of the two lines segments, achieving the ability of hyperacuity. Theoretically, the proposed circuitry is able to resolve smaller

differences than the human hyperacuity limit, but in a real retina the cell mosaic does not show this high regularity and drift also has its own variability in velocity and direction. These effects may limit the resolution of the mechanism.

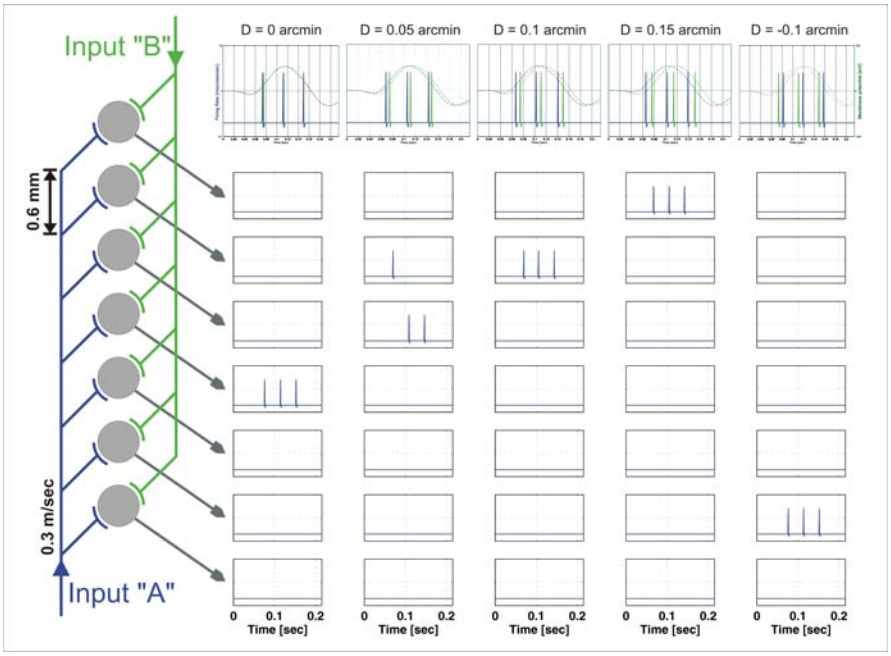

Figure 9

Simulation example. On the left side the simulated place coding network is presented. The top row shows the ganglion cell responses regarding to the different stimuli. The firing patterns of the place coding circuitry are presented in columns.

It is important to note that this model is bio-inspired, since it does not provide evidence for the existence of this mechanism in the primate brain, but only proposes a biological concept for achieving visual hyperacuity.

6 Discussion

Our model raises several new questions that we are unable to answer at present. It is evident that a kind of place coding mechanism would strongly depend on the drift direction and velocity. If drift velocity is too slow, or drift direction is far from perpendicular to the line segments, the time differences between firing patterns can exceed the half of the P cell minimum inter-spike interval, resulting in a false detection. The problem can be solved by repeating the detection process with a different drift velocity and/or direction.

There is no evidence for a mechanism that would adjust the drift characteristics in hyperacuity tasks, but it is known that drift shows high variability – reaching maximal velocity values several times per a second [68] – and it is at least indirectly influenced by visual factors [40]. Furthermore it is known that human performance improves with practice (perceptual learning) in hyperacuity tasks [61, 24]. If we assume that perceptual learning have some effects on drift direction and/or velocity then it would explain why learning improvements are highly specific to task, stimulus type, orientation, retinal location and eye trained [56, 23, 43], and why improvements in one task diminish after a similar task has been subsequently practiced [56, 52].

Another open question is the structure of the proposed neural circuitry. If human visual hyperacuity is based on a place coding circuitry, then which exact neural network may serve this function and where does it possibly takes place in the visual pathway?

The internal delays in our proposed circuitry fall in the range of milliseconds, which can be ascribed to both long axons and "delay neurons". The slowest unmyelinated axons with *~0.1 um* diameter have about *0.3 m/s* conduction velocity. The place coding circuitry (shown in Figure 9) needs about 3-4 mm length of this type of axon. Without suggesting a possible location in the visual cortex, we note that this axon length is conceivable. Similar lengths were observed in layer 2/3 of striate cortex, where pyramidal cells extend long axons that form clustered projections linking iso-orientation columns [20].

It is important to note that in our model, the resolution of hyperacuity is related to the number of place coding neurons, which is evidently independent of the ganglion cell density, while acuity is directly related to ganglion cell density. It well correlates with the observation that hyperacuity tasks appear to be limited by the extent of striate cortical representation both in the fovea and in the perifoveal field [36, 66, 67], while contrast and resolution tasks seem to be limited by ganglion-cell density [62, 48, 49].

Conclusions

In this work we propose a new theory about human vernier hyperacuity. The theory states that an involuntary eye movement – the ocular drift – is ideal for converting a small spatial offset (which is unresolvable by the photoreceptor mosaic) into a time offset between firing patterns, which is already resolvable by a place coding neural circuitry. Similar circuitry has been found in owl's brain achieving auditorial hyperacuity. In our theory, the perceptual learning has a possible role in adjusting drift direction, duration and velocity to the hyperacuity task. As far as we know, this is the first theory that assumes such an important role to the ocular drift in hyperacuity tasks.

In a computational example we show that the existence of the proposed mechanism is plausible. The theory raises several new questions that we are

unable to answer at present, but we hope they may serve suggestions for further research.

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Software Measurement Activities in Small and Medium Enterprises: an Empirical Assessment

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Abstract: An empirical study for evaluating the proper implementation of measurement/metric programs in software companies in one area of Turkey is presented. The research questions are discussed and validated with the help of senior software managers (more than 15 years' experience) and then used for interviewing a variety of medium and small scale software companies in Ankara. Observations show that there is a common reluctance/lack of interest in utilizing measurements/metrics despite the fact that they are well known in the industry. A side product of this research is that internationally recognized standards such as ISO and CMMI are pursued if they are a part of project/job requirements; without these requirements, introducing those standards to the companies remains as a long-term target to increase quality.

Keywords: metric; measurement; small-medium size enterprise; ISO; CMMI

1 Introduction

It is an established fact that software metrics play an important role in ensuring the quality of software products. However, it is also observed that many software companies are not implementing any software metric programs in their organisations, as those programs are suggested. Further, the studies reveal that more than 70% of software products were developed in small- and medium-scale software companies [1]. There may be more than one reason for this; as a start we look at the definitions: in 1990, IEEE closes a gap in defining measurement standard by the following definition: "a standard that describes the characteristics of evaluating a process of product" [2]; following that, in about less than 10 years,

IEEE [3] defines measurement as "the act or process of assigning a number or category to an entity to describe an attribute of that entity." Those definitions are not controversial, nor they are misleading; however, they indicate that measurement in software engineering may not be always objective as it is different to other established branches of engineering. It is because each branch of engineering is based on basic fundamental principles of physics, but it is not so straightforward up to now to establish principles and rules for measuring software. The ongoing researches in establishing such fundamental rules and large amounts of different type of measurement techniques reported in the literature support the nature of this challenge.

The variety in measurements is induced by subjectivity, which is partially due to aiming to measure the quality of software, such that, there are software metrics, which are measure for quality attributes. Software quality metrics [3] can be treated as functions whose inputs are software data and whose output is a single numerical value that can be interpreted as the degree to which the software processes are a given attribute that affects the software quality. Further quality attributes include maintainability, flexibility, testability, usability, integrity, efficiency, reliability, correctness, interoperability, reusability and portability, which are closely related to software metrics [4].

Software metrics have potential roles at different scales in all type of information systems. Most of the companies, regardless their type, such as in government, banking and finance, education, transportation, entertainment, medicine, agriculture, and law sectors, all use software products. Naturally, maintenance (corrective, adaptive, perfective, preventive) is required for each software system on a regular/irregular basis. In such activities, the software metrics can be used for assessing the proposed modification and improvements in software systems.

Defining the problem

Metrics not only help us to evaluate a system, but they also give us ideas that help us in decision making, and they can be utilized for scheduling and planning, and for estimating costs. What we have represented so far led us to think about the practical uses of the software metrics in the industry. It is a common observation that normally large companies take initiatives to achieve quality objectives, but small and medium sized enterprises (SMEs)/companies may put quality on a lower rank, even if it is not explicitly said so. If we compare the ratio between large and small companies, especially for software companies, small and medium enterprises are dominant in producing software products when compared to large companies. For example, 77% of the software companies in Germany in 2000 were small scale [1]. Similarly in Brazil, 69% of the software companies were small scale in 2001. This data supports that most of the software products were produced by small and medium scale software companies. Hence, software companies of small/medium size are not to be underestimated and addressed separately.

The following are the research question and its sub-questions, which motivate us to make an effort to study this issue.

The research question arises: Are metrics and other tools used by the SMEs companies for achieving quality in their products?

The sub-question are as follows: If they (or some of them) are using them, to what extent are they using them? (1)

Are they using throughout the software life cycle, starting from the requirements stage through to the deployment of the software; or are they only using them for reviewing purposes (software inspection/review) and testing? (2)

2 Literature Survey: Measurement and Metrics in Software Engineering

The term *software engineering* was first defined by Fritz Bauer[1] in the 1960s "as the establishment and use of sound engineering principles in order to obtain economical software that is reliable and works efficiently on real machines". Since then, software engineering has been widely accepted as an engineering branch, and measurement has been seen as an important aspect of it, as there is an engineering principle that measurement is a mandatory task [5]. With the popularity of this branch, ongoing research is continuing on this topic with the following examples. In [6], the authors argue that measurement information should be properly processed and classified in order to provide a "better" overview of the current situation. Another example is reported in [7], where the practical problem of the applicability of measurement theory in software engineering is underlined, despite the fact that measurement theory gives a scientific base. In that work, the author discusses the challenge to propose a measurement theory for software engineering, and they approach the problem by coining the concept of weak measurement theory to solve the basic problem for the applicability of measurement theory in software engineering. Wang [8] has also attempted to apply measurement theory in software engineering. However, his work is not complete and we could not find the extended works on Morasca's nor Wang's on measurement. Related to measurement theory, Kaner has proposed a framework for the practical evaluation of software metrics in [9], which provides a more formal approach to the other existing ones.

[1] From the memoirs of Brian Randell, editor of The 1968/1969 (first) NATO Software Engineering Conference

In addition to those articles, there are several books in literature devoted to measurement theory. It would be beneficial to quickly visit them as we refer to them later in the paper.

The first book on the measurement of software was, to our knowledge, introduced by M. H. Halstead [10] in 1977. This work was bookmarked as a theory of software science, and it established the first analytical laws of computer software. In his proposal, Halstead developed quantitative laws using a set of primitive measures. Halstead's measurements are considered interesting because they can be applied after the design or completion of code. After that publication, successive books on software measurement are reported in the literature. For instance, 'A framework on software measurement', [11] by Zuse takes the theoretical, practical and evaluative view of software measurement. This book investigates software measurement principles and provides the proper guidelines for software measurement. The author evaluated all the existing measurement proposals for software at the time of writing and pointed out their pros and cons and their practical applicability to problems and, accordingly, he suggested a "proper" way of measurement. In addition to measurement, metrics are also researched in the literature; for example, 'Software Metrics' by Fenton and Pfleeger [12] is devoted specifically to software metrics; in the work, the authors discuss measurement in a comprehensive way, from the basics of measurement theory to its applicability to software engineering, which is required for software development. They explain the fundamentals of measurements and experimentations in general and software engineering measurements. Furthermore, the authors emphasize planning for measurement programs, measurement in practice, and metrics tools.

Among the popular recent books, 'Software Engineering, a practitioner's approach' [13] by R. S Pressman, is one of the base books in software engineering. This is a book which can be treated as a bible in software engineering, as it discusses many aspects of software engineering; without going into too much detail, those are most of the facets of software engineering starting from software process to the latest software development practices. By taking the measurement as the key element in engineering process, the author reports his work on applying different measurement techniques through examples. In addition, two specific chapters are devoted to software product and process metrics in the book, which are used for different languages, stages, applications and types of development.

Another recent example is Software Engineering by Sommerville [4], which is also a valuable contribution, as it provides different measurement techniques at different stages of the software and for different applications. Similar to Pressman's book, this book is not limited to specific measurement techniques. A remarkable detail of the book is, for example, that it proposes reliability metrics[2].

[2] Chapter nine: critical system specification

In some of the books, practical applications are discussed, and they provide valuable knowledge through the experiences of applying software metrics; 'Software process improvement: metrics, measurement, and process modeling', [14] edited by Haug, et al. is one of them. This book is devoted to reporting authentic applications of measurements and to analyzing measurement techniques, which are applied to software process improvement. As experimental data, the authors have collected a set from the European Experience Exchange (EUREX) project sponsored by the European Systems and Software Initiative for Software Best Practice in Europe.

Those books are among the most famous examples that deal with software measurements and metrics; they are widely accepted in the software engineering community. The discussion on measurement in software engineering is not limited only to those examples that we have visited briefly; it still continues. Those examples show that there have been many metrics proposed for different purposes in the software engineering domain; there are works such as [15] and [16], aiming to compile already proposed metrics. At the same time, particular implementations of measurement techniques for improving quality in small and medium scale organizations are in limited number to our knowledge.

3 Definitions of Measurement and Measurement Standards

Before we go further, we would like to define metric and measurements definitions that we adopt in this work.

A metric is formally defined as "a quantitative measure of the degree to which a system, component, or process possesses a given attribute" [2]. A "measurement" is then a task which computes a metric from the attributes of the entities within a given domain, using clearly defined rules [5]. Metrics must be purpose-oriented [17] and have clear objectives [18].

With the examples we have given so far, the role of measurement in software engineering proves itself as an essential to understanding software processes. In parallel to this claim, Bourque and colleagues [5] argue that software engineering without measurement would be hard to interpret, because without measurement, management would be difficult. According to [17], measurement is essential to monitor, understand and improve software processes as well as products and resource utilization. While those points are given credit, there are other researchers (e.g. Basili [19]; and [15] and [17]) who point out that there is a lack of consensus around software measurements. In fact, many metrics have been defined which are not used, according to [17]. While metrics need to be goal- or purpose-oriented, a goal must first be determined, along with a way of measuring the degree of

attainment of the goal, and both tasks may be subjective. For example, counting the "lines of code", as a metric, may serve to as an indication of the complexity of a system. However, line count is not a measure that provides any insight into the activity of a system, as not every line of code has the same relevance at run-time. The number of lines of code has also been claimed to be inappropriate for component-based systems; rather, complexity metrics for such systems should be based on number of components and interactions among them [20], [21].

Specifications of the rules for the process of quantification may also be ambiguous [17]. For instance, the implementation of the same metrics in different software tools to support assessment of software design has been found to give different results [22].

Furthermore, there are some software attributes that are a challenge for measurement in IT domains at various levels. For example, the elements in the IEEE standard concerning the evaluation of productivity are broad-ranging and dynamic, such as documents per person per hour or lines of codes produced per day [23].

Another important topic is productivity and its assessment. Metrics connected with productivity of IS have been controversial [24], [25]. It has been argued that traditional metrics of input versus output can work "... as long as computers allow firms to produce more of the same product at lower costs..." [26]. Such measures of productivity concentrate on the efficiency and effectiveness of the systems [27]. Overall performance measures include operational performance, especially system availability and throughput (that is, producing the output within specified time boundaries, and the quality of the content of output). However, the benefits of IT may not always be easy to measure as they can be in forms such as customer service or convenience, which may be intangible. Hitt underlines the contribution of IT to business productivity but claims there has been mis-measurements of output [28]; for instance, where customer service or convenience are the output, there are difficulties, as well as subjectivity, that may lead to mis-measurement.

An early summary of what we have reviewed so far tells us that there are no generally accepted metrics for many qualities, such as class cohesion in software development, which address software quality when new features are added; this prediction is supported in the literature (e.g. [29]). It has also been argued, in the case of software complexity, that measures are not only subjective, but that they do not satisfy a theory of measurement [30], and this charge can be laid against many IT measures.

In the end, the literature pushes us to question if it is possible to objectively measure all useful qualities of software. There are approaches to this problem. Attributes have been divided into categories of external and internal, according to whether they are indirectly or directly measurable, respectively [31]. External metrics are most likely to be subjective. More explicitly, internal attributes, such as defects, can be measured, for example by counting, while an external attribute,

such as maintainability, can be measured only with the help of internal attributes which act as surrogates, such as measuring modularity with a count of components. Another internal metric is "lines of code", which is simple to implement by counting, whereas "effort" required producing those lines is difficult to determine and so is an external attribute which can only be approximated by surrogate measures, such as "development time".

There is a great deal of literature on the measurement of external attributes in software development, software quality and software maintenance [31]. Many of the metrics proposed in the literature are directly or indirectly related to structural connections between the number of classes, the number of times a class is invoked, and class size, which are all internal attributes. These measures are used as surrogates in measuring external attributes such as how flexible or reliable a system is.

Another important aspect of the software products is maintenance. Measurement and metrics are important for assessing proposed maintenance activities in software systems. As the business requirements change over time, further maintenance activities are performed. Those activities are not limited to changes in the hardware of systems but can also be change in the code, which may create a risk of instability in the system; this degradation is referred to as code decay, which is the decrease of the quality of the code due to further modifications [32], but the degradation of systems needs to be measured through the observation of activities required to add new functionalities or new hardware, or repairing faults. An indirect measure of system decay proposed in [33] involves the relative effort, time to complete, and quality of modifications. To quantify the effect of aging in operating system resources, various metrics such as "estimated time to exhaustion" have been proposed in an attempt to develop proactive techniques to limit system crashes. The "time to exhaustion" metric suggested in [34] is based on the slope estimation of the resource usage on UNIX variants and can be applied to different system resources including free memory and file table size. Another approach [35] focuses on estimating resource exhaustion through time series analysis, where they create artificial workload to the web server and monitor the resources for applications involving web servers.

When it comes to the reliability, it also requires measurement, as software quality is strongly tied to it. Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time as defined by IEEE [2]. The literature on reliability measures is not newly emerged. One of the earlier works on software reliability measures identifies mean time to failure and cumulative execution time as surrogate measures. [36] and [37] proposes assessment techniques based on errors remaining after the testing phase, as well as on failure and hazard rates. Those errors may be captured later via user feedback; meanwhile, errors and failures remain the main elements in measuring reliability (e.g. [38], which is a revised version of [39]) although inclusion of measures of software complexity, test effectiveness and the consideration of the

complete operating environment have been recommended to make reliability assessment more accurate [40].

Coming back to the subjectivity of the measurement in software engineering, we remark that Fenton identifies reliability, maintainability and productivity as the quality attributes of high level software, and he notes that maintainability and reliability are attributes of the software itself, whereas productivity is an external attribute associated with people (the organization) dependent on processes and software [18]. He claims that the use of internal software attributes to measure these external attributes remains subjective. For example, modularity may or may not be considered a surrogate for maintainability. The metric of class number may be taken into account more when modularity is considered, because the increased number of classes allows for greater precision in expressing dependencies [41].

By definition, metrics have been developed to measure aspects of software development. For example, productivity of a development team provides a measure of delivery of maintenance activity [42]. Modularity and a system's resulting flexibility are important for further maintenance. As with other software metrics, the objectives of a software development project shape the criteria for their evaluation. In some environments, speed of development is critical, in which case a low number of classes may be desirable because the development team is rushing to produce software within a tight time frame. A related adverse by-product may be that the production rate for lines of code per day is high because of the duplication of code elements. Conversely, when future maintenance is considered to be important, the metric of class number may be useful because the increased number of classes allow for greater precision in expressing dependencies [41], despite a lower production rate of lines of code per day because more design thought is put into the software construction.

As seen from this quick review of the literature, the topic of measurement/metrics is not a narrow topic and one must comprehend the details of the metric in order to employ it, including the circumstance for which it has been proposed; this makes measurement/metric proposals not always straightforward. Such complexity may discourage SMEs in the software industry, where time and human power are usually precious. The good news is that there are some internationally recognized standards in parallel to this issue.

3.1 International Standards

So far, we have provided and discussed our literature survey to do with software measurement and metrics. Through this report we can deduce that software measurement and metrics are not only challenging, but they also can be controversial, subjective and open to discussion. Despite those handicaps, there are some standards which have international reputation. For instance, the capability maturity model integration (CMMI) is presently accepted as the best

accreditation for the software industry. Some of the CMMI certified organizations are Boeing's Space Transportation System software, Tata Consultancy Services[3], Telcordia Technologies[4] and Granter Inc.[5] By adopting the CMMI, automatically, they consider the best practices of measurement in their processes.

With the International Standards Office (ISO), providing ISO9001 and ISO9000-3, companies can have two more standards to certificate and authenticate their work. ISO 9001, which is a standard for any type of product, was basically not for the software industry, but its application to software was initiated by TickIT (UK), which provides the methodology for adopting ISO 9001 to the software industry. As a figure, in 2002, 1252 organizations in 42 countries were accredited by ISO 9001 (TickIT) (in 2002) (www.iso.org, www.isoqar.com/iso9001/ qualintro.htm). ISO 9000-3 explains how ISO 9001 can be applied to software. ISO 9000-3 (http://www.praxiom.com/iso-9000-3.htm) provides the guidelines which lead and serve as an all-inclusive standard for the software industry. ISO 9000-3 is used in developing, supplying, installing, and maintaining computer software. For acquiring the ISO 9000-3 certification, an organization must develop the organization's software quality assurance (SQA) team, implement the organization's SQA systems and undergo certification audits.

Standards on metrics and measurements are not limited to these examples; recalling that this paper aims to shed a light how much the measurements and metrics are adopted in SMEs, we discuss this limitation in a literature survey on standards in the last section.

4 Research Methodology

For the purposes of our research, the attributes which are deemed to be of interest in the literature on metrics are more important than the form of the metric and measurements. In seeking an answer to the research question, we have reviewed discussions on the objectivity and complexity of the applicability of the measurements/metrics. The literature we have surveyed caused us to think on whether the SMEs use measurement as a tool in their business or not. In the case that they are using them, we aim to learn about how much they benefit from them.

4.1 Research Framework

This research adopts a two-stage approach to address the research question.

[3] http://www.tcs.com/homepage/Pages/default.aspx (accessed in 2010)

[4] http://www.telcordia.com (accessed in 2010)

[5] http://www.gartner.com/technology/home.jsp (accessed in 2010)

Firstly, we formed a body-of-knowledge including software metrics and measurements. As Figure 1 shows, while reviewing the literature, we saw that an empirical study would help to fill the practical applications of the measurement/metric in SMEs in the software domain; and we identified the research question accordingly. Later, with the preparation/modification of the interview questions, we saw that approaching the research question via sub-questions would ease and increase the validity/reliability of the research.

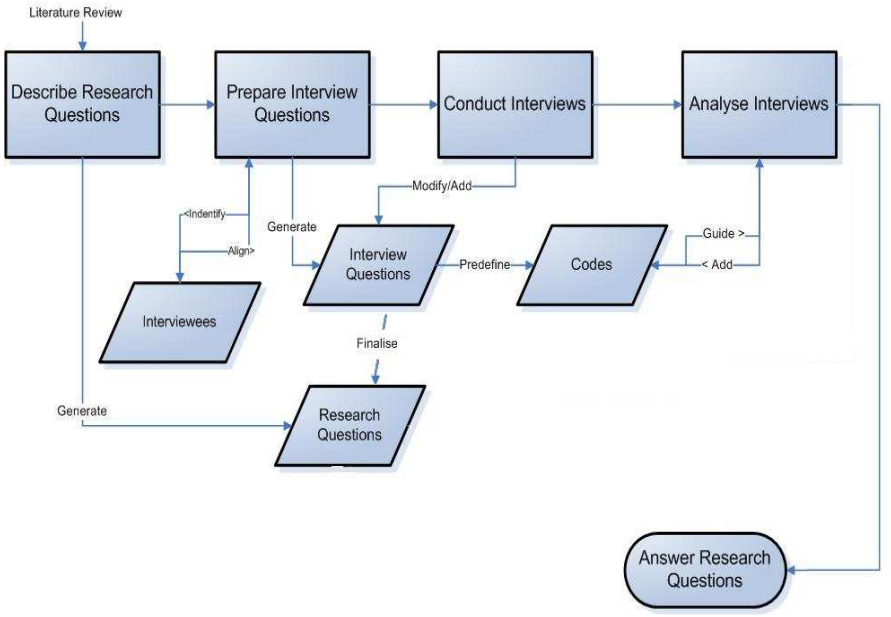

Figure 1
Research Framework

Given the qualitative nature of the research, we have selected to conduct semi-structured interviews to collect data from the field. The preliminary questions are based on the literature survey and the gaps we identified to our knowledge.

We started looking for local SMEs to approach software developer firms in Ankara as potential key informants, who later discussed the validity of the preliminary interview questions. As a selection criterion, those key informants[6] have considerable knowledge and experience on software engineering in the industry. With the fourth and the fifth informants delivering similar comments and advice, we decided to stop aligning questions and look for interviewees.

[6] For privacy reasons, we do not mention the names of the key informants, nor any identifier that can reveal their workplaces.

The second stage of the research is based on the aligned semi-structured interview questions from the previous stage. Those aligned questions formed the main discussion points with the interviewees. Similarly, these interviewees were selected from different companies with the selection criterion of being senior professionals in their fields.

Additionally, we added the analyses of semi-structured interviews and ranks which we collect from the interviewees to this data pool in order to design, revise and validate our research (Figure 1). This way of doing research fits into the grounded theory of Glaser [43], i.e. research where the data collected during the research guides the research.

Before going to the interview sections we selected keywords as codes to be used while analyzing the free comments of the interviewees. Those codes accelerated our analyses to cluster quotes under similar topics.

As these steps indicate, this qualitative research is designed as a descriptive study rather than an explanatory one, and it adopts partially grounded theory and interviews as research techniques.

4.2 Collection, Analysis and Interpretation of the Results

All the questions were finalized and validated by chief executives in established software companies' in Ankara. First, we interviewed these executives and, based on these discussions and their recommendations; we redesigned our questions and sent them to be validated through e-mails. After their modification, the following set of the questions and their scope were finalized and summarized, as in Table 1.

Table 1

Survey questions and their scope

Q. No.	Questions	Scope
1	How many software professionals are you employing?	1-5 / 5-10 / 10-20 / 20-50
2	How many of those s/w professionals are working with you more than 2 years?	Stability of the employees in particular industry
3	What is the average experience of your s/w professionals not only in your place but in the industry?	Average experience of software professional
4	How many core team members are aware about the usefulness and importance of software measurements to achieve quality objectives?	Experience and awareness of team members for measurements in software Industry
5	Which tools and methods are you applying for achieving quality objectives?	Knowledge of tools for quality measurements
6	Does the company use software measurement as tool in the business?	Applicability of measurement tools for quality measurements

7	Have you got any measurement guidelines/framework for controlling/assessing your products' quality?	Awareness and availability of measurement tools
8	In terms of software development, are you using any internationally recognized standards for achieving quality objectives and to improve your business? For example, ISO, IEC, CMMI.	Availability and applicability of international standards
9	If you already have any of those standards, did they help you to improve your company up to your expectations? If so, in what aspects?	Effect and results of using international standards
10	Do you think CMMI is a criterion to assess a company's quality and reputation?	Aim of adopting highest standard for a company
11	Which type of measurements are you using? Could you please name few of them e.g. resource management of computer, number of: line of code, loops, modules, errors...etc	Specific metric for measurements
12	Has the company got expert team or members who are software quality engineer or experienced in software measurement; if so, how many? Do you hire any person outside for this activity, alternatively?	Availability of software quality engineers
13	In the full software development cycle (from requirements, through design, development, testing, to deployment) are you using any kind of measurement?	Use of measurement Techniques in software life cycle
14	Do you give more importance to inspection or testing your products? In other words, do you do assessment while inspecting or testing?	Software review/inspection
15	Where else are you using measurements; e.g. maintenance or support to you clients?	Further use of measurement
16	Are you following quality guidelines/frameworks/ measurements while doing business with your partners?	Use/effect of measurements in business
17	Do you think that software measurement can improve the quality of your products? Please provide an example while answering.	Actual knowledge and awareness of quality objectives
18	Do you think there are additional/alternative tools/methods than software measurements in order to improve your business in software development?	Awareness of other tools for improving quality and level of company

After finalization of the questionnaire, the interviewing technique (section 4.1) is adopted for examining the applicability and awareness of software measurement and metrics in software companies located in Ankara. We collected the list of software development companies from METU-Technopolis[7], a place inside a leading university of Turkey, Middle East Technical University, where the offices of approximately 280 companies are located. Of those companies, more than 90% are SMEs operating in the ICT (60%) and electronics (25%) industries. As we mentioned earlier, most software is developed in small/medium-scale companies. This practice is more common in developing countries, but it also found in developed countries such as in Germany. We considered companies which between 5 and 50 software developers as small- and medium-scale companies. We aimed to interview only those companies in this category; hence we visited about half of the listed software companies.

5 Observations

We have a general interpretation of the results that shows at the first glance that SMEs are not inclined to put the measurement at the first rank, which is in parallel with [17] what has been discussed previously. Despite the fact that there is a considerable amount of metrics proposed in literature, these tools are not considered; some of them are not even known among the interviewed companies, although they are actively doing business with a variety of clients (from defense to accountancy).

We have not found encouraging results regarding measurement for achieving quality objective in their software programs. Most of the companies have ad hoc evaluation criteria in their software development programs. Their main aim is to complete and deliver the job as soon as possible because they are tied to strict time frames. For this reason, most of the companies failed to answer our survey questions with details, as there are no specific measurement/metrics programs implemented in their organisations. The most they do is that, in the case of failure or complaint, they try to remove the errors.

At a small set of companies, the organisers found interested in measurement and metrics. The appendix has a sample set which shows the feedback from the interviewees.

We have been informed that not applying measurement techniques is not only because of reluctance but also it is considered as “not necessary” and “not required” in their project contracts.

[7] http://www.metutech.metu.edu.tr/cms/index.php?Lang=EN (accessed in 2010)

Although the role of measurement in software engineering is given credit and still remains as one of the popular topics in the software domain, SMEs do not see any "persuasive" benefit to urge them to study, evaluate and choose measurement techniques and metrics to adopt in their workplaces. This observation may be seen as challenging what we have recovered in the literature survey e.g. [5], [15], [17] and [19]; however, feedback from relatively larger software companies shows that measurement becomes a necessity in order to monitor, understand and improve software processes along with software products and resource utilization as the companies get larger in the number of employees. The following feedback is from relatively larger companies.

> *"Definitely, yes, (s/w measurement can improve quality of the product). The outcome of the measurements can be used as input in following projects; hence, more suitable project scheduling is possible, which makes the application correct and high-quality" (interviewee 5, noe (number of employee): 20-50)*

> *"Yes (s/w measurement can improve quality of the product). With measurement the tasks can be planned and managed. Staff can be educated with the composite metrics" (interviewee 11, noe: 20-50)*

> *"Yes (s/w measurement can improve quality of the product), we identify spots to rehabilitate and we take preventive actions with the aid of measurement" (interviewee 13, noe: 80)*

Pretty much all of the companies informed us that the quality of the products should be assessed by the developer, the team leader and/or through meetings for software inspection/review. However, to achieve quality standards, none of the interviewees has put any metric or measurement techniques forward. In a broader sense, most of them do not use any measurement tools in their business, except some who limit measurement to evaluating jobs in price:

> *"…we calculate e.g. 33 hour requirement for the client" (interviewee 17, noe: 5-10)*

Because quality is strongly tied to measurement in software products, as we have surveyed in the literature, we attempted to collect more information about the quality standards from the interviewees. The result is that the following internationally recognized standards (such as ISO, CMMI) are beneficial in general; however, adopting such methodology requires time and patience:

> *"An increase in quality but slowing development due to procedure" (interviewee 4, noe: 1-5)*

Another observation is that even simple metrics such as lines of code are open to discussion:

> *"Yes, (s/w measurement can improve the quality of the product) but cannot be single criterion alone; e.g., the number of LOC was 200 in a*

> *program we wrote 10 years ago and the performance was poor. Later, we reduced it to 3 LOC and it runs correctly and fast. Here, less LOC brought an advantage through speed; however, higher LOC may not be a disadvantage; at the same time, it should run correctly. Another example is that we have delivered a project with 10 forms although we have been contracted for one form. Here, some of the forms were simple while the others were a separate project each. Those numbers became important while negotiating on price" (interviewee 16, noe: 10-20)*

Obtaining an internationally recognized certificate is not an easy task. However, those certificates are not always obtained because the company would like to make the work place "better" and/or up to a standard, but rather because they are required in project specifications. While discussing the role of CMMI we collected the following feedback:

> *"CMMI is a very important criterion but not sufficient alone. The course could be left after obtaining CMMI" (interviewee 5, noe: 20-50)*
>
> *"… it (CMMI) may stay as a label and not be applicable logically and efficiently for small companies" (interviewee 6, noe: 10-20)*
>
> *"CMMI cannot always be followed; a company can flex it according to internal dynamics" (interviewee 14, noe: 10-20)*

6 Results, Discussion and Recommendations

Recalling our survey of discussions on the absence of consensus on software measurements [15] [17] [19] [22] we predicted a reluctance to use metrics in the industry. This is gets more complicated with controversial and subjective proposals in productivity measurements [24] [25] [28]. Similarly, maintenance is seen as one of the most important activities in software systems, but indirect measurements provide subjective and system-specific solutions [33] [34] [35]. Also reliability, hence error-failure measurements, are important [36] [37] [38]. In addition to these, assessing the developer team [42] is another measure. Coming along with the metrics and measurements, popular international standards (CMMI, ISO9001 and ISO9000-3) stand as common criteria to maintain quality levels in software companies.

6.1 Results

As summarized and clustered above, we prepared our interview questions (section 4.2) to address the motivation for measurement and tools to measure productivity, reliability, maintenance, developer teams and to address the awareness of international standards.

We concluded the following results in conjunction with our observations (section 5):

Measurement is not a priority unless it is money-oriented (1)

For small companies, until they get some financial benefit/support, they do not implement any specific measure to improve quality.

The use of measurement is limited in the assessment of software (development) quality and it is considered a long term activity (2)

Most of the SMEs have the perception that software measures are only used for improving quality, but that it requires a long time to implement in the workplace.

Measurement and metrics are limited due to the unawareness of measurement techniques amongst the developer (3)

In fact, there is a considerable confusion about what the measurement activities are for in improving quality of the product. They know the fundamentals, that a code should be reviewed and metrics should be applied, but not which specific tools and techniques should be applied at different stages of software development; most of them are not aware or interested. This is closely tied to result (1) as financial benefits are seen as main motivator in the industry.

The use of software metrics is limited due to heavy time pressure for the delivery of products (4)

This is also a hard truth for the software industry and especially for the SMEs, who are considerably affected in achieving quality objectives due to heavy time pressure, as they are often working on projects with tight timeframes.

The use of software metrics is limited due to lack of highly experienced professionals in the company (5)

In SMEs, there are several constraints, including (and maybe led by) financial constraints. To achieve quality objectives, any company must have experienced professionals in permanent positions or must hire them for some specific activities, e.g. software inspection/review. However, financial constraints are a barrier to doing so. Further, changing organizations amongst software professionals is not an uncommon practice; when software developers gain some expertise in a specific area, they get offers from bigger industries with better packages; hence, it is not uncommon for small companies to lose those employees who become experienced in evaluating measurement and metrics..

The uses of measurement techniques are limited due to an unawareness of the depth knowledge of quality issues in the software development process (6)

Before joining the software industry, most, but not necessarily all, professionals come from universities with an engineering degree. However, in most of the syllabi of engineering branches, quality issues are not given emphasis in the

course curriculum. Even in computer engineering, software quality management is not an essential part of the study curriculum unless the student chooses to take such elective courses.

An obtained standard or certificate may be used just as a label (7)

It is not uncommon to require standards such as ISO or certificates such as CMMI as a prerequisite in project specifications. In order to have a chance of entering the pool of companies tendering for projects, companies are motivated to apply such standards/certificates. However, after getting involved in projects, the certificate may stand on the wall and the company does not necessarily follow its directives.

6.2 Recommendations

This paper presents our survey of SME measurement activities used to achieve quality objectives in their software products. Although improving the quality of software seems to be a prime objective in the industry, our survey reports that most SMEs do not spend as much care as is encouraged in the literature. This study also hints at the effects of an absence of consensus regarding software measurements and, as a result, an associated reluctance to use metrics in the software industry. On the other hand, neglecting quality objectives bears the risks of delivering low quality software; obvious consequences are not only the rejection of the projects but also a poor reputation for the software company, an important element in the long term for any developing company.

Apparently, the bringing of the metric/measurement notion into a workplace may increase budgets for projects and/or reduce short-term earnings because adopting a notion in a company requires stability (keeping adoption with changing employees and projects) and separate documentation for knowledge management for further projects to apply similar measurements. However, our study supports the view that it is not only our suggestion that SMEs adopt the measurement and metrics in their software development program, but also that those companies give credit to this practice.

Keeping in mind that this paper has limitations while focusing on the application of quality methods specifically, the reader should be informed that this report should be read in conjunction with related literature on quality in the software domain. Software quality issues include the application of the measurement methods, but it is not limited to this; for example, while getting into more technical detail, the quality of the applied algorithms and program code are given credit generally in the literature. Recent examples include [44], where the author underlines the performance linked to those two items while developing software products.

Conclusion and Future Work

As following discussion of results and limitations indicate there is room to research to itemize the reasons linked with the findings of this study.

Adopting metrics/measurements in SMEs is not an easy task, as we mention in Section 2. Hence, blaming those companies for not doing so would not contribute to a solution and would leave the recommendation unsupported. Rather, proposing a way to adopt metric/measurement applications could encourage SMEs to get motivated in this topic. For such an attempt, a framework of IT, project management and economics may generate a method of approach to introduce the idea of metrics and measurement within SMEs in a long-term, step-by-step approach.

When proposing such a method, the limitations of the results presented in Section 6.2 should be considered. A general limitation is that we have conducted interviews locally. However, this limitation is not a great constraint as the companies present a broader variety of interest as we mention in Section 5. Another one is that we had only one person per company to interview. Most SMEs have a limited number of employees; for this reason we do not expect any considerable variety of information within a company. However, obtaining information about the employees' degrees and their course curricula could extend results (3), (5) and (6) as a more focused questionnaire could be prepared to investigate their knowledge on metrics and measurements.

The current study did not have the chance to study project requirements in order to analyse the details of results (1) and (4). We are aware that as a part of the industry, there are many companies working on delivering bespoke information systems. However, we have excluded this issue in this study. This limitation opens an associated and further study on project-based investigation in SMEs.

The current study gives signals that although some companies have acquired internationally recognized certificates and standards, they may not follow them, as summarized in result (7). As we have observed, standards may be used only as labels. We see the potential for future studies focused on revealing more concrete reasons for delaying obtaining these standards.

Appendix: Sample set from the interviews

1	2	3	4	5	6	7*	8	9	10	11	12	13	14	15	16	17	18
10,20	12	4	4	CMMI based	no	a	ISO, CMMI	Extraordinary change in SE. Especially while having a project in defense. As a result of std., things are getting easier like repeating, inspecting and adding.	yes		1 quality eng.	Sub-versioning is used related to configuration management	Inspection is important, testing is still on the developer	Measurement in maintenance	When we are sub-contractor, yes.	No programming measurement is used, yet.	
1,5	1	1,4	all	No time to apply	No time to apply	d	Not yet		yes		no	Eclipse IDE and integrated SVN	testing		no	Definitely yes	
1,5	1	1,5	2		yes	a, b, c	ISO	Increase in quality but slowing in development due to procedure	no	Resource management, loop, module, error counts	1	We use our program developed here	Both in inspecting and testing	Maintenance and support to client		More quality products thanks to minimized errors; less problems with the clients	
20,50	10	3,4	all	ISO, CMMI	Screen, code and sql line count	b, c	We use ISO and working on CMMI	Yes, increase in quality, software reverse ratio increased, code library is more productive	CMMI is a very important criterion but not sufficient alone. The course could be left after obtaining CMMI.	Code line, error, database table counts	2 software quality eng.	MS TeamSystem, Foundation Server	More on the inspection phase		Yes, quality guidelines and document templates	Definitely yes. Outcome of the measurements can be used as input in following projects hence more suitable project scheduling is possible, which makes the application correct and quality.	
5,10	3	1,3	all	ISO 9001:2000, tools and methods defined within our quality management.	TS 12207	a, b, c	ISO		yes				both	Customer support	yes		
5,10	6	7,8	1	We don't use	We don't use	a	No		Yes	We don't use	No	No	Test	We don't do measurement	No	It may without doubt	No comment
1,5	2	10	1	Source controlling, regular testing	No	a, c	No		No	Source management, error count	2, we provide this service, too	No, we develop ourselves	Test				Unit testing
20,50	10-20	8	We have ISO; majority knows	We follow ISO quality standards	We don't use tools	c	We follow ISO quality standards	Yes, it made us to work more productive and in an order.	Certainly it is an important criterion	LOC, # of modules, ratio of compile time error to runtime errors	1	Enterprise Architect	Both of them are important equally for us.	We don't have currently.	Yes	It increases quality of the products.	
20,50	35-40	5	15	Agile, Atlassian JIRA, Continuous Integration	JIRA	a, b	ISO, SPICE	Beneficial indirectly. Measuring and time frame provide essential benefits	No	We have non-integrated solutions (see 13)	5-6. we have consulting firm working of quality.	Total lines, LOC, comment lines, DP, DP/LOC (see 11)	Testing and continuous Integrations are more important	We do measurement on every field, including support and sale.	Yes	Yes, with the measurement the tasks can be planned and managed. Staff can be educated with the composite metrics.	Continuous Integration time frame. Testing automation .
10,20	6	4	all	We follow approach compatible to CMMI	no	c	Because the company is small we don't have any certificate but we try to follow standards e.g. ISO	-	CMMI cannot be followed always; company can flex it according to internal dynamics	We follow RUP life cycle. We test speed and security of the program	3 people	Enterprise Architect	In both	During instalment to the client	yes	Yes, we ensure re-usable codes to save work power	-

* (a)The developer himself checks the quality with available tools (b)The team leader checks the quality regularly (c)Meetings are organized to evaluate the quality of code, (these meetings are called software inspection or software review) (d)The company only bothers about the output i.e. if programs produce the output without any bug or error, no matter how the code is built (e)Any other

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Advanced Examination of Zinc Rich Primers with Thermodielectric Spectroscopy

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Abstract: Zinc-rich primers (ZRPs) are widely used coatings for corrosion control on steel surfaces. Usually ZRPs use high zinc concentration in the paint and a little amount of organic resin used as a binder. Commonly, two fundamental protection mechanisms operating in ZRPs can be recognised, namely the galvanic protection and the barrier effect. The high zinc content can secure cathodic protection to the base metal, and the zinc corrosion products can make the barrier effect. In this research study, the cathodic corrosion protection capabilities of zinc rich alkyd primers prepared with different spherical zinc dust volume concentrations (0-20-40-60-80% by weight) are tested. The mechanical, electrochemical and dielectric properties are measured in order to find a correlation between these and the protection capabilities of the coating.

Keywords: zinc-rich primers; thermodielectric spectroscopy; cathodic protection; alkyd resin

1 Introduction

Zinc-rich coatings and primers have the unique ability to provide galvanic protection to the steel surfaces to which they are applied. These coatings have a large amount of metallic zinc dust combined with the binder. ZRP's binder is usually an organic resin such as epoxy, alkyd or urethane. After the proper application of a zinc-rich coating to a steel substrate, the binder holds the zinc particles in contact with each other and the steel surface. This contact between two dissimilar metals, when in the presence of an electrolyte, will form a galvanic cell. The zinc particles become the anode in the galvanic cell, and the steel substrate serves as the cathode. Galvanic action causes the zinc to be corroded while the steel is protected from corrosion attack. Zinc-rich coatings are unique in that they provide protection to the steel surface even with voids, scratches, pinholes and other small defects in the coating system.

The basis of the cathodic protection by a zinc-rich paint to a steel substrate is the electrical conductivity between the zinc particles in the coating and between the zinc particles and the steel substrate. [1-2]

The protection mechanisms of ZRP coatings are the following [3]:

- During the formation of the galvanic cell between the base metal and coating's zinc particles, the base metal will have cathodic protection.
- The corrosion products of zinc particles will be deposit on to the base metal, where they will appear as a corrosion inhibitor.
- The corrosion products of zinc will transform into basic zinc-carbonate (4 $ZnO{\cdot}CO_2{\cdot}4H_2O$), which will act as a pore sealant.
- The Zn particles are able to bind the acidic components which will result in a higher pH environment.

During galvanic protection the valuable base metal is connected to a more negative corrosion potential (less noble) metal. This system results in a "short circuit" galvanic battery and the current between the metals will secure the necessary cathodic polarization of the protected metal if the rate of contacted surface areas is necessarily good. In the ideal situation, the outer resistance (R_O) of the system is zero and the inner resistance (R_I) is also very close to zero. (*Fig. 1*)

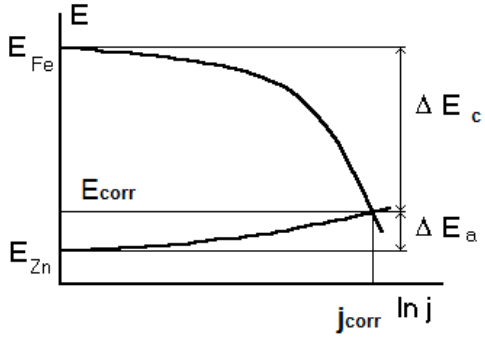


Figure 1

The potential-current diagram when $R_O = 0$ and $R_I \approx 0$

If the system resistance is bigger, ($R = R_O + R_I$) for example, if a poor conductivity material is placed ($R_O \neq 0$) between the two metals (Zn and Fe), or if the conductivity of the electrolyte around the metals is large ($R_I >> 0$), then the protection current is limited by R resistivity. When R is growing, there is a point where the current is not enough to cause cathodic polarization. (Fig. 2)

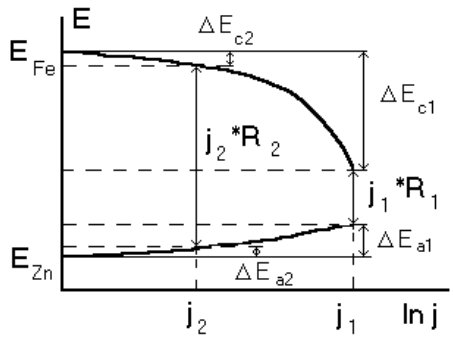


Figure 2
The potential-current diagram when $R_O \neq 0$ and $R_I >> 0$

As already stated, in zinc-rich coatings and primers, the Zn particles must contact with each other and with the base metal. The coating should be a relative good conductor. In ZRPs the cathodic protection appears only in the beginning, when the surfaces of the zinc particles don't deposit by ZnO, and the pores are not saturated by Zn corrosion products. The oxidation of Zn particles to ZnO and their transformation to basic Zn-carbonate can be considered a barrier effect.

Another important factor that influences the ZRPs protection characteristic is the size and shape of the zinc particles added to the primer. The added zinc particle's shape can be spherical, lamellar or mixed. As other research studies have shown, the lamellar zinc (or mixed) provides better protection to the base metal. The smaller particle sizes provide better anti corrosive properties. [4-6]

When elevating the zinc pigment volume concentration (PVC) a point can be reached called critical pigment volume concentration (CPVC) where there is a just sufficient polymer matrix to wet and fill the voids between the individual particles. At PVCs below the CPVC, the composite consisting of pigment particles is randomly embedded in a continuously connected matrix of polymer. Above the CPVC, there are void structures in the film due to insufficient polymer, but the pigment particles can still be thought of as continuously connected. The polymer is still continuously connected globally, but voids will cause the polymer to lose local connectivity, and thus the sharp drop-off in the mechanical properties of the coating just above the CPVC. Above the CPVC, a new fluid phase – air – will be present in the film and its properties are drastically affected, especially its density, transport, mechanical, and optical properties. [7]

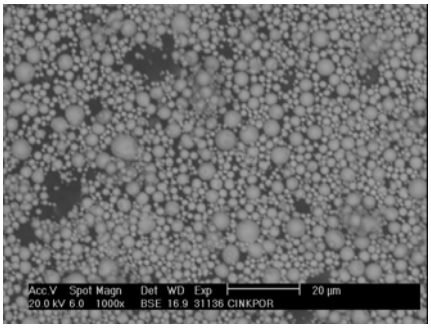
The CPVC depends on the resin and pigment type and other additive materials. In ZRPs when lamellar shape zinc particles are used, this is a much lower value (~40-50%) than when spherical shape zinc is used (~70-80%). [8]

2 Experimental Work

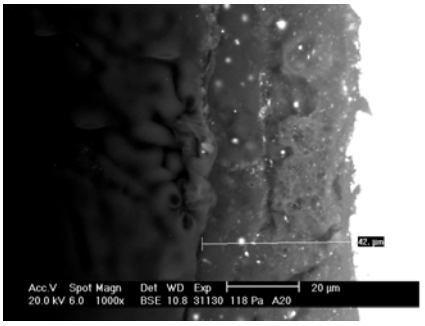
Model coatings were made – with different concentrations of 1-5 µm diameter spherical shape zinc dust of an alkyd resin – and applied onto clean steel plates with film casting frame to examine the protection capabilities of ZRPs. The zinc contents were 0-20-40-60-80-90% by weight. After at least two weeks of conditioning, samples of the same thickness were selected (75±5 µm) and measured by the following techniques:

- Thickness measurement with MINITEST 500 equipment,
- Flexibility with Erichsen cup test,
- Hardness with Königh pendulum (compared to glass standard),
- Dielectric properties with thermodielectric spectrometer [9] between 20-200 °C temperature range and between 0,1 – 100 kHz frequency range,
- Electrochemical measurements with Solartron SI1287 electrochemical interface,
- Scanning Electron Microscopy (SEM) with Philips XL30 ESEM.

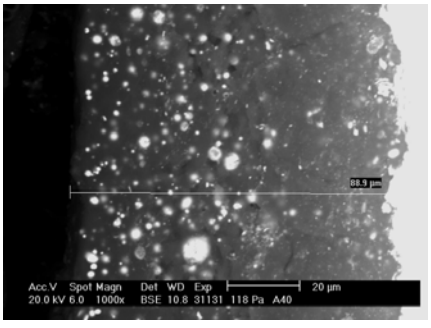
The cross-sections of the prepared samples are shown on *Figure 3* with the examination of SEM. (The base metal is on the right side.)



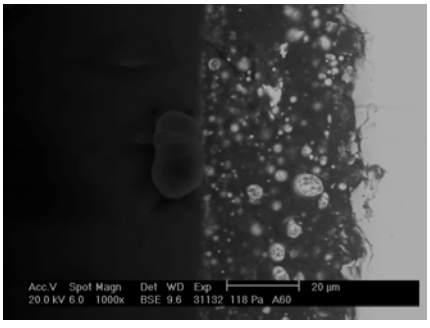
The used Zinc-dust particles



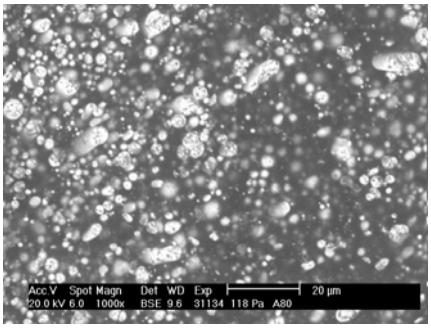
Alkyd resin with 20% Zn dust content



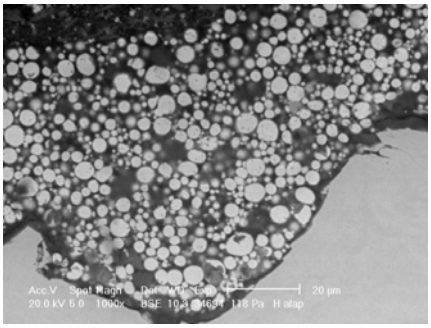
Alkyd resin with 40% Zn dust content



Alkyd resin with 60% Zn dust content



Alkyd resin with 80% Zn dust content



Alkyd resin with 90% Zn dust content

Figure 3
The SEM pictures of the prepared samples' cross section

The ZRP structure changes when more zinc dust is added to the base resin. Therefore, the dielectric properties also change, since they are directly related to each other. With the use of thermodielectric spectroscopy the dielectric properties such as relative permittivity can be measured in the function of temperature and frequency. In organic polymers, different kinds of polarizations can happen when we put them into an electric field. The most important one in our case is the dipole orientation polarization, which can be characterized by its activation energy at the relaxation temperature. Its dependence on temperature and frequency following the Arrhenius equation:

$$\frac{1}{\tau_r} = \omega_r = A \cdot \exp\left(-\frac{E_A}{RT}\right) \tag{1}$$

where: τ_r is the relaxation time [s],

ω_r is the angular frequency of relaxation [s^{-1}],

E_A is the activation energy of the orientation process [$J \cdot mol^{-1}$],

R is the universal gas constant [$J \cdot K^{-1} \cdot mol^{-1}$],

T is the temperature [K],

A is the pre-exponential constant.

In *Figure 4* the measured thermodielectric spectra can be seen for different Zn dust content measured at 100 kHz. Unfortunately, the highest Zn content coating (90%) cannot be measured because of short circuit in the dielectric cell. Therefore, this is not examine further.

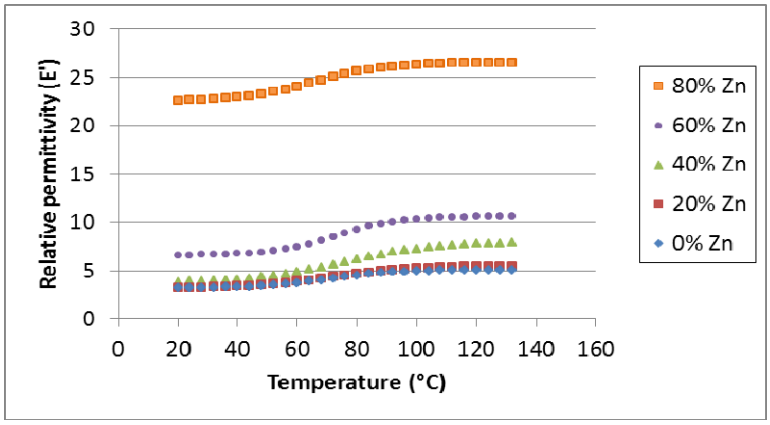


Figure 4

The measured thermodielectric spectra for 100 kHz frequency

When the zinc dust content of the coating was elevated, the relative permittivity also increased slowly below CPVC and rapidly above CPVC. In the following *Table 1* the measurements are summarized and the averaged results can be seen.

Table 1

The results of the measurements

Zinc content (m/m%)	t_R *(°C)*	E_A *(kJ·mol^{-1})*	*Flexibility (mm)*	*Hardness (%)*	*Relative permittivity (ε')**
0	65	94,4	9,8	20	4,2
20	69	233,2	3	60	4,3
40	78	241,1	2,8	65	6
60	72	310,7	1	69	9
80	64	405,3	0,2	74	25
90	-	-	0,1	81	-

*For the f=100 kHz thermodielectric spectrum's relaxation temperature.

The dielectric properties – the activation energy of the dipole orientation (E_A) and the relative permittivity – reveal the polymer matrix to be more rigid when the zinc content is elevated. The dipole orientation's relaxation temperature (t_R) does not change so much. The mechanical properties change consistently; so flexibility decreases when the hardness rises with the elevated zinc content. Furthermore, with this examination an unknown sample zinc-content can be estimated.

During standard corrosion examination a 5 mm cross defect was made on the coated steel plates, which were covered with a 3% NaCl solution and left for ten days (*Fig. 5*) in order to check the presence of protection with the measurement of circuit potential.

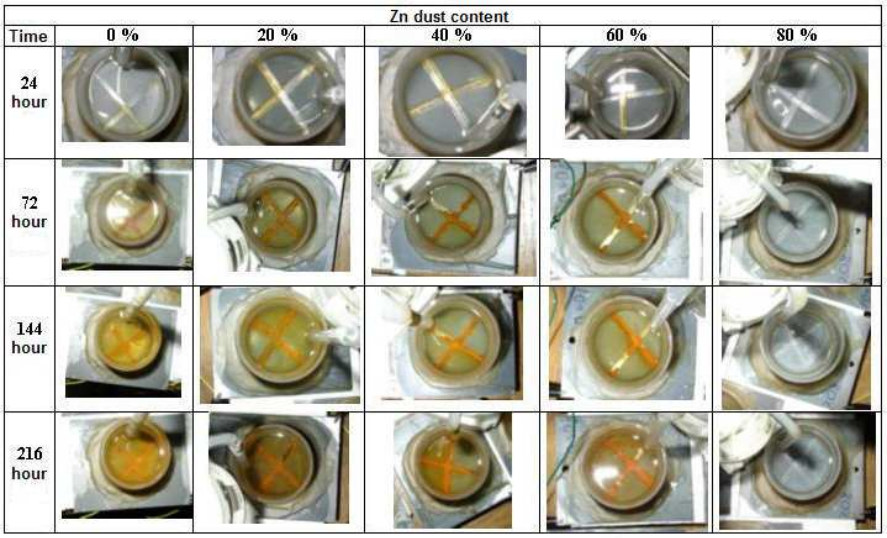


Figure 5
The cross damage test of the different zinc content ZRPs

Only the high zinc content (80%) coating provided sufficient cathodic corrosion protection, since during the ten days of the standard corrosion examination only this sample was free from iron corrosion products. During this type of electrochemical measurement only the 80% zinc content coating shifted the potential to a lower value compared to the others. (*Fig. 6*)

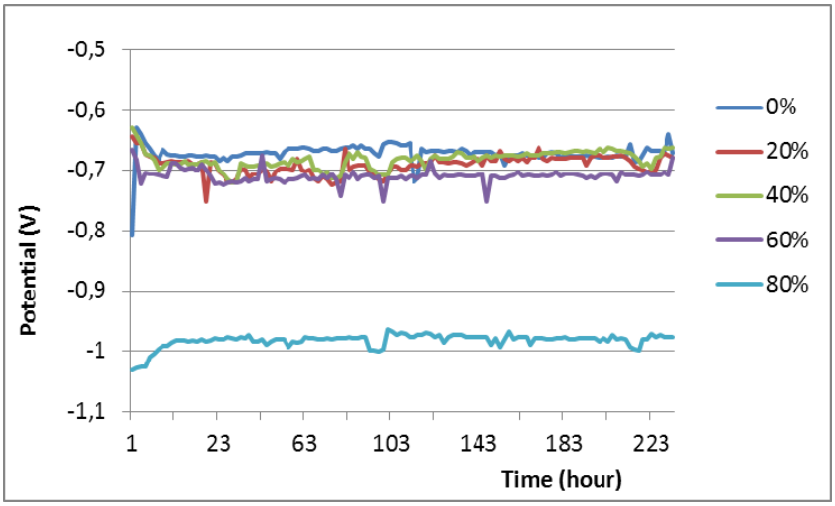


Figure 6
The potential (vs. SCE) measurements of the different zinc content ZRPs

In the case of the prepared samples, the low zinc concentration ZRP coatings cannot support cathodic protection to the base metal. This as well can be seen on the cross section pictures since when the zinc content is low, no zinc particles were connected to the base metal. We can only see this protection effect above 80% zinc dust weight concentration, as has been proved in other papers as well. [9-11]

Conclusions

Thermodielectric spectroscopy was found to be a useful tool for assessing the cathodic protective behavior of ZRP organic coatings. The higher the zinc content we have in a ZRP the higher will be the activation energy of the dipole orientation. Therefore, the thermodielectric measurements can be used for zinc content estimation. Above CPVC, the dielectric permittivity increases rapidly, and thus it is also easy to check this value with TDS. A good cathodic protection can only be achieved with high Zn dust content coatings, which also result in high relative permittivity. During our experiment, we found (in our case) that the Zn dust amount should be higher than 80% in the dry weight in order to support cathodic protection. This results in 5~6 times higher relative permittivity of the protective coating (~25) than alkyd binder's alone.

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Statistical Syllable Analysis for Pronunciation Ambiguity Detection and Resolution in Text-to-Speech Synthesis Applications: A Case Study in Turkish

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Abstract: In this study, pronunciation ambiguity in Turkish is considered. A syllable-based ambiguity detection/resolution framework is proposed for Turkish text-to-speech synthesis applications. For this purpose, first the pronunciation ambiguity cases are identified. Such cases are classified into 7 main groups. Statistical analysis on the occurrence rate of these main groups is performed by means of the examination of meaningful Turkish texts. This first level analysis shows that especially the syllables ending with vowels (particularly with a, e and i), which are potential ambiguity sources, have significant occurrence rates. Next, the granularity of the frequency analysis is escalated to distinct syllable level. For the so-far-identified 154 exceptional syllables, the occurrence rates are computed. The results of this study will constitute a major baseline for pronunciation ambiguity detection in Turkish. The resolution of these ambiguous cases will certainly require a large lexicon. The results will also serve as a guideline for the prioritization of data inclusion to such a lexicon (i.e. lexicon enrichment) for rapid coverage. Our distinct syllable level analysis results show that by inclusion of all the words having the 100 most frequent exceptional syllables, it is possible to resolve 99% of pronunciation ambiguities in Turkish. To our belief, the findings of this study might also be applicable and useful for other languages.

Keywords: Text-to-speech synthesis; natural language processing; grapheme-to-phoneme conversion; less studied languages; pronunciation ambiguity

1 Introduction

Text-to-speech synthesis has been a popular research area with various purposes, such as increasing the 'humanity' in the user interactions of multimedia appliances, or aiding people with visual impairments, etc. Research studies devoted to the Indo-European linguistic family, particularly English, constitute the major portion of text-to-speech synthesis applications. Text-to-speech synthesis

studies on Turkish, which started in 1990s and currently continue in academic and commercial areas, are relatively low in quantity compared to most other languages. In almost three decades, various researchers have directly or indirectly contributed to the literature regarding Turkish text-to-speech synthesis via a M. Sc. Theses [1]-[18] and Ph. D. Dissertations [19]-[20] in addition to the relevant conference proceedings [21]-[31] and journal papers [32]-[36].

For most of these publications, the general focus is on items at the signal processing level, such as the proper unit selection, concatenation, etc. Among them, some (e.g. [15], [18]) have particularly dealt with applicability of the synthesis techniques on mobile devices, some others (e.g. [12], [19], [22], [25], [26]) have concentrated on the duration modeling, whereas some (e.g. [14], [28]) have focused on achieving prosody in the synthesized speech. On the other hand, the number of studies focusing on pronunciation disambiguation is very limited. In this subject, due to their approach of identifying and handling the examples, [24] and [32] can be considered as biblical resources. Moreover, they provide almost a complete set of interesting cases for ambiguities in Turkish pronunciation. In [20], a statistical approach for pronunciation disambiguation was proposed. In [31] and [36], additional exceptional cases (i.e. cases for which pronunciation ambiguity occurs) in Turkish were discussed; a practical framework for pronunciation ambiguity resolution was proposed.

The main motivation of this study can be summarized as follows: For Turkish text-to-speech synthesis applications, the need for the creation of a pronunciation lexicon together with a rule set is unarguable. As long as this lexicon is enriched, the pronunciation accuracy of a text-to-speech synthesizer depending on this infrastructure (i.e. the lexicon and the rule set) would get better. The first step in achieving a robust infrastructure would be to identify the problematic/exceptional cases, which have already been done in [31] and [36]. In this study, we carry out the next step, which is nothing but the determination of the correct order of lexicon enlargement for rapid coverage (i.e. the ideal order of inclusion of exceptional syllables in order to achieve maximum pronunciation ambiguity resolution capability with minimum effort). In other words, our aim in this study is to identify which cases are encountered most frequently in daily used Turkish language. To our belief, the results of this study will serve as a guideline for following research studies about the prioritization of lexicon enrichment.

The outline of this paper is as follows: After this brief introduction section, in Section 2, we will try to revisit the main cases where pronunciation ambiguity occurs in Turkish; and at the same time classify them. In Section 3, we will give the results of the statistical analysis of the occurrence rates of the identified 7 main groups. In Section 4, we will increase the depth of this statistical analysis by considering the so-far-identified 154 syllables distinctly. Section 5 will include comments and discussions about the analysis results together with potential future work.

2 Pronunciation Ambiguity in Turkish

2.1 Historical Background

Even though it is claimed that "the current Turkish alphabet is phonetic" (i.e. the grapheme-to-phoneme mapping is one-to-one), especially for the words imported from foreign languages, such as Arabic, Persian and French, many occurrences of one-to-many grapheme-to-phoneme mappings can be found [36]. Certainly, the complexity of the grapheme-to-phoneme mapping is not as dramatic as in French or in English (e.g. there exist many unpredictable pronunciations in these languages such as the pronunciation of the 4-gram "ough" in the words "rough", "cough", "dough", "tough", "though", "through", "thorough"). Moreover, as demonstrated in [31] and [36], it is possible to handle almost all exceptional cases in Turkish by means of accent signs, which are introduced on vowels. On the other hand, regardless of its complexity, it is unarguable that the occurrence of pronunciation ambiguities constitutes a considerable ratio.

Regarding the phonemes in modern standard Turkish, there have been several studies [37]-[39] which have been performed by experts of linguistics. All these studies agree on the fact that the number of phonemes is much more than the number of symbols in the current Turkish alphabet. In one of the most respected studies on this subject [39], 44 phonemes have been identified. On the other hand, the current Turkish alphabet, which is based on the Latin alphabet, consists of 29 letters. During the adoption of the Latin alphabet in 1928 (the so-called "Alphabet Revolution"), though there were proposals of 32-letter alphabets, a set of 29 letters was considered to be sufficient [40].

In addition to 29 letters, an accent sign (i.e. "^") was considered to be necessary and sufficient. This sign used to have multiple purposes: increasing the duration of the current vowel in some occasions (as in the word "`bâriz` (obvious)", for which the duration of the letter a is longer than normal), palatalization of the preceding consonant (as in the word "`kâğıt` (paper)", for which the letter k is palatalized), or both (as in the word "`kâbus` (nightmare)", for which the letter `k` is palatalized and the duration of the letter a is longer than normal). Presently, this accent sign has become almost obsolete in practice due to two main factors: (i) untruthful rumors that the usage of this accent sign was cancelled by the Turkish Language Council in 1980s, (ii) for written communication, the wide-spread usage of media (such as e-mail, SMS, etc.) which did not support the accent sign.

For human readers, who perform pattern recognition and resolve pronunciation ambiguities automatically (and unconsciously), the pronunciation ambiguities do not constitute a problem in Turkish as in some other languages. On the other hand, when the speech is synthesized by machinery, the introduction of some mechanisms (for the machinery to identify these ambiguities) becomes compulsory. Otherwise, the quality of the synthesized speech would be irritating

for the listeners; and it might even yield lexical and/or syntactical misunderstandings in some cases.

2.2 Cases of Pronunciation Ambiguity

As stated before, in most of the studies conducted so far, pronunciation ambiguity in Turkish has not been handled, or not even mentioned. For example in [29], the authors claimed to obtain reasonable synthesized results. On the other hand, since they did not mention pronunciation ambiguity in Turkish, how they achieved what they claimed is a big question mark.

In [31] and [36], exceptional syllables (i.e. the syllables for which the grapheme-to-phoneme conversion mapping is one-to-many) have been identified as follows (Throughout the following items, the example words are given in syllabified form in order to provide better understanding, especially to the non-Turkish speaking readers):

1) Syllables ending with the letters a, e, i, o, u, ü: In such syllables, the relevant letter might be pronounced normally (e.g. as in the words a-tak (attack), e-tek (skirt), i-nek (cow), o-to-büs (bus), u-fuk (horizon), ü-mit (hope)); or in lengthened form (e.g. as in the words a-şık (lover, folk poet), me-mur (government officer), i-kaz (warning), li-mo-ni (lemonish), u-di (lute player), mü-min (religious person, believer)).

2) Syllables ending with the digrams al, ol, ul: In such syllables, the letter l might be pronounced velar (e.g. as in the words al-kış (handclap), bol (numerous, copious), dul (widow)); or alveolar (e.g. as in the words al-kol (alcohol), gol (goal), ma-kul (reasonable)).

3) Syllables starting with the digrams la, lo, lu: In such syllables, the letter l might be pronounced velar (e.g. as in the words la-la (life-coach of the Ottoman Prince), ba-lo (party, ball), o-luk (groove)); or alveolar (e.g. as in the words lam-ba (lamp), fi-lo (fleet), bil-lur (crystal)).

4) Syllables starting with the letters k, g: In such syllables, the relevant letter might be pronounced velar (e.g. as in the words kar-tal (eagle), ga-ga (beak); or palatal (e.g. as in the words ka-ğıt (paper), ga-vur (giaour)).

5) Syllables ending with the digram at: In such syllables, the digram at might be pronounced normally (e.g. as in the words kat (floor, flat), yat (yacht)); or softly as if there is the phoneme e in between (i.e. similar to the aet triphone but in a rapid manner) (e.g. as in the words sa-at (clock), sıh-hat (health)).

6) Syllables starting with the digram na: In such syllables, the digram na might be pronounced normally (e.g. as in the words nar (pomegranate), naz (whims)); or softly as if there is the phoneme e in between (i.e. similar to the nea triphone but in a rapid manner) (e.g. as in the word ma-na (meaning)).

7) Syllables ending with the digram el, em, en: In such syllables, the letter e might be pronounced normally (e.g. as in the words bel-li (definite), em-zik (pacifier), en-gin (profound)); or widely (e.g. as in the words bel-ge (document), ma-tem (mourning), mü-ren (muraena)).

As described above, for these exceptional syllables, generally there exist two different pronunciations. On the other hand, it should be noted that some syllables might fall into more than one category according to the classification given above. For example, the syllable ka belongs to the 1st and the 4th classes at the same time. As a result of this, there exist four different pronunciations of this syllable for different occasions:

1) kaba (rough); for which the letter k is pronounced velar, and the letter a is pronounced normally.

2) kabiliyet (capability); for which the letter k is pronounced velar, and the letter a is pronounced in lengthened form.

3) kağıt (paper); for which the letter k is pronounced palatal, and the letter a is pronounced normally.

4) katip (clerk); for which the letter k is pronounced palatal, and the letter a is pronounced in the lengthened form.

2.3 Proposed Method and Architecture for Pronunciation Ambiguity Detection/Resolution

As stated and demonstrated via numerous examples in [32], for complete and accurate pronunciation ambiguity resolution in Turkish, it is compulsory to perform syntactical analysis in addition to lexical analysis (e.g. for some miscellaneous cases such as the pronunciation ambiguity resolution of isographic words; for example the word sol (left), for which the letter l is pronounced velar; and the word sol (musical note G), for which the letter l is pronounced alveolar).

On the other hand, since Turkish is an agglutinative language, syntactical analysis is a very complicated task. Due to this fact, in [36], a practical method for pronunciation ambiguity resolution (without rigorous syntactical analysis) has been proposed. Certainly, this method would not be able to perform the resolution of some miscellaneous cases such as the isographic words; but it is able to resolve the problems listed in Section 2.2 (such as the identification of the syllable bal in the word bal (honey), for which the letter l is pronounced velar, and in the word istikbal (future), for which the letter l is pronounced alveolar), which constitute the majority of the pronunciation ambiguity problems in Turkish. Moreover, it should be noted that for some cases, syntactical analysis by itself would not be sufficient; more advanced and intelligent methods for contextual

identification might be. (E.g. for the resolution of the statement "Karlı bir yıl geçirdik [We experienced a very profitable/snowy year]", the context of the overall text shall be identified. If it is a text about the meteorological information, the word kar shall be identified as kar (snow), for which the letter k is pronounced normally; if it is about finance, then the word kar shall be identified as kâr (profit), for which the letter k is palatalized.)

In [36], the symbology seen in Table 1 was proposed in order to achieve a phonetic representation. Examples regarding the usage of this phonetic representation are listed in Table 2.

Table 1

Proposed additional symbols and their definitions (according to [36])

Normal	Letter pronounced normally	Aa	Ee	İi	Oo	Uu	Üü
Long	Letter pronounced in a longer manner	Ââ	Êê	Îî	Ôô	Ûû	ßÿ
Thin	Inside a syllable: - The a, o, and u letters succeeding the alveolar l letter; - The a, o, and u letters succeeding the palatal k or g letters; - The a letter included in the na diphone, which is pronounced as the nea triphone.	Áá	–	–	Óó	Úú	–
Long and Thin	The a and u letters satisfying the conditions of being "long" and "thin" simultaneously.	Ãã	–	–	–	Ýý	–
Soft	Inside a syllable: - The a, o, and u letters preceeding the alveolar l letter; - The a letter included in the at diphone, which is pronounced as the aet triphone.	Àà	–	–	Òò	Ùù	–
Wide	The widely pronounced e letter.	–	Ëë	–	–	–	–

Table 2

Examples regarding the usage of the proposed symbols in [36]

	a	**e**	**i**	**o**	**U**	**ü**
Normal	araba (car)	etek (skirt)	inek (cow)	otomobil (automobile)	uzun (long)	ütü (iron)
Long	âşık (lover)	têmin (obtain)	îkaz (warning)	limônî (lemonish)	ûdî (lute player)	mÿmin (believer)
Thin	láma (llama), káğıt (paper), gávur (giaour)	–	–	lómboz (porthole)	billúr (crystal), sükút (silence)	–

Long and Thin	lãle (tulip), kãbus (nightmare), yegãne (unique), mânã (meaning)	–	–	–	ulýfe (salary of the soldiers in the Ottoman Empire), sükýnet (silence)	–
Soft	ihmàl (ignorance), itaàt (obey)	–	–	gòl (goal)	kabùl (acceptance)	–
Wide	–	dirhëm (drachmai)	–	–	–	–

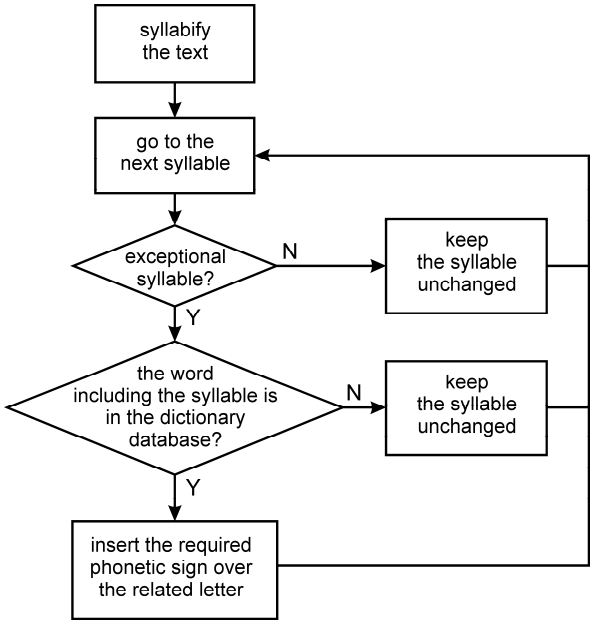

Figure 1
Flowchart of the proposed pronunciation ambiguity detection/resolution methodology

The proposed method for pronunciation ambiguity resolution is straightforward, as seen in Fig. 1. The prerequisite for complete/correct performance of this method is the existence of a lexicon identifying the pronunciation of the words including exceptional syllables. The algorithm syllabifies the text to be synthesized. One by one, it controls whether each encountered syllable is exceptional or not. If a syllable is exceptional, and if the word containing that syllable is inside the lexicon (in case that such a lexicon is constructed), then the pronunciation of the relevant syllable is identified to be exceptional. The very basic structure of such a lexicon is given in Table 3.

Table 3
The structure of the pronunciation lexicon and some examples

Exceptional Word	Number of Exceptional Syllables	Exceptional Syllable Position(s)	Pronunciation(s) in Relevant Syllable(s)
`arazi` (field)	1	{2}	{1}
`makul` (reasonable)	2	{1,2}	{1,3}
`samimi` (sincere)	1	{2}	{1}

The fields of such a lexicon can be explained as follows: Each row of the lexicon contains a separate word; the number of exceptional syllables in that word, and the positions of these syllables. The pronunciations of such syllables are coded by means of an enumerated type (e.g. 1 standing for the lengthening of the vowel, 2 standing for palatalization of the consonant at the beginning, 3 standing for alveolarization of the consonant at the end, etc.). By means of such a structure, it is possible to model the words containing more than one exceptional syllable (such as `makul` (reasonable), represented and pronounced as `mâkùl`); or the words containing a unique syllable more than once, whose occurrences are pronounced differently (such as `samimi` (sincere), represented and pronounced as `samîmi`; or `hakiki` (real, original), represented and pronounced as `hakîki`).

At this point, it should be noted that even though the pronunciation check/control activity is based on syllabification and syllables, the framework does not imply that the speech synthesis shall be concatenative and syllable based. In other words, the proposed method can be integrated with any speech synthesizing technique.

Another remark is the possibility of extension of this lexicon by introducing new columns, such as the positioning of the intonation and stress for prosody in speech synthesis.

3 First Level Statistical Analysis and Results

As stated in [41], language statistics have a quite important role in speech synthesis and recognition applications for high fidelity. In this chapter, we try to give figures of merit about how frequently the exceptional syllables occur in the Turkish of daily life. For this purpose, we have parsed 48 books (short stories, novels, essays and scenarios written by several amateur and professional writers) including a total of 1,529,647 words.

As the basis of the statistical analysis in this study, we implemented a so-called "syllable hunter" script in MATLAB, which depends on the syllabification algorithm defined in [36]. The main idea of this algorithm is based on determining

the locations of the vowels through the words, since each Turkish syllable contains one vowel. The algorithm also handles the syllabification of some imported compound words, which linguistically have Latin origins (e.g. `elektronik` (electronics) to be syllabified correctly as `e-lek-tro-nik` but not as `e-lekt-ro-nik`). Our "syllable hunter" gets each word one by one from the parsed source text and extracts the syllables into a syllable pool in accordance with the flowchart given in Fig. 2.

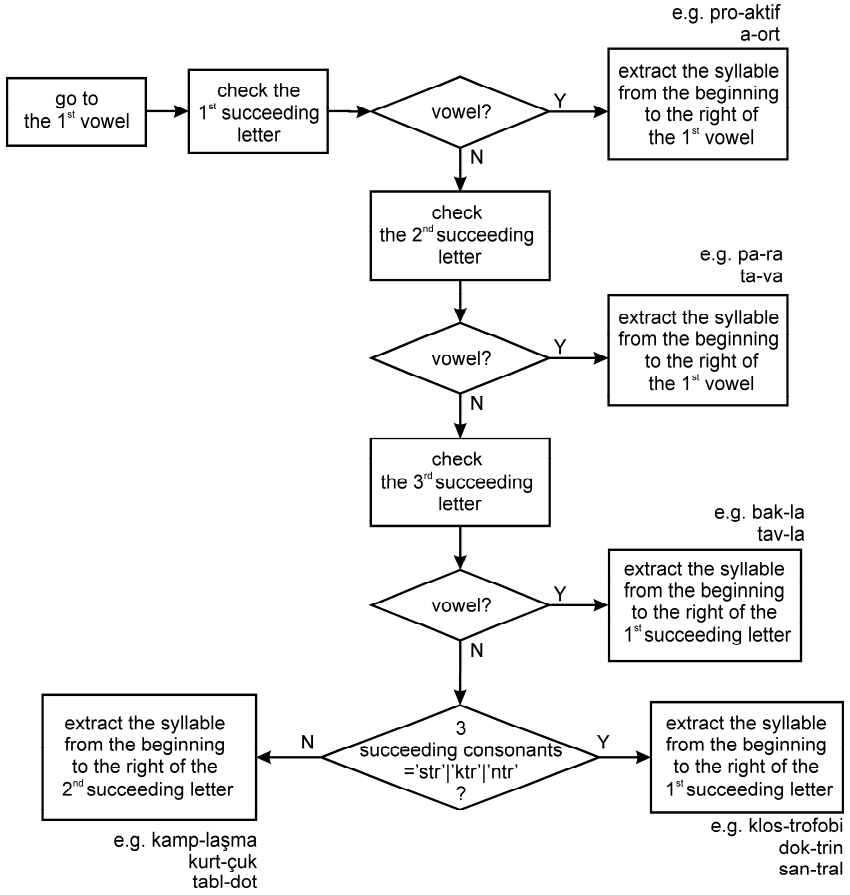

Figure 2
Flowchart of the syllabification algorithm for Turkish [36]

By means of the "syllable hunter", we syllabified the entire word-set, and obtained all the distinct syllables together with their numbers of occurrences in the processed texts. We found that the aforementioned 48 books contain 4,043,954 syllables in total. Next, we analyzed the syllables in order to obtain the statistics of the exceptional syllables, where the exceptional syllables were identified according to the rules given in Section 2.2.

As a second step, we classified the syllables into four different groups according to their lengths. In Turkish, a syllable might consist of at least 1 letter, and at most 4 letters. In recent years, some words with 5-letter syllables (e.g. `tvist` (twist), `frenk` [French or more generally European, Western], etc.) have been imported and adopted. But since the occurrence rate of the 5-letter syllables is relatively small, we have not considered them in this study.

The charts in Fig. 3 depict the overall syllable distribution statistics of the processed texts in this study, comparatively with [29]. Except the 5-letter syllables (which have been ignored by us), it can be seen that our results are in almost perfect agreement with [29]. This means that our data constitutes a sufficiently-large set, over which confident statistical analyses can be performed and meaningful results can be obtained.

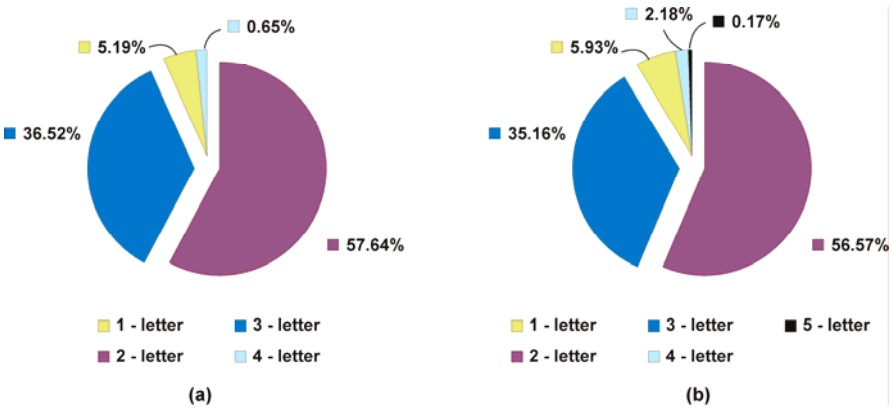

Figure 3

Overall syllable distribution statistics: results of this study (a) vs. [29] (b)

Table 4 shows how frequently appear the syllables ending with the letters ‘a, e, i, o, u, ü’ as separately and as a whole. Due to phonological features of Turkish, syllables ending with vowels constitute the majority. Hence, it is not surprising for us that more than 51% of all possible syllables end with these 6 vowels (As a matter of fact, the remaining 2 vowels `ı` and `ö` are not as frequent as `a` or `e`). On the other hand, it is apparent from Fig. 3 that about 57% of syllables are 2-letter. Thus, having the 2-letter syllable dominance in this class is expected. Moreover, the majority of the 2-letter syllables belonging to this class are the ones ending with `a`, `e` and `i`. These will be investigated in detail in the upcoming Sections.

Table 4

Frequencies (%) of the syllables ending wıth the letters ‘a, e, i, o, u, ü’

	1-letter	2-letter	3-letter	4-letter	Total
'a'	1.4813	15.7036	0.0214	0.0003	17.2066
'e'	0.6360	12.3194	0.0149	0.0002	12.9705

'i'	1.1519	10.0035	0.0170	0.0002	11.1726
'o'	1.1845	1.5677	0.0203	0.0001	2.7725
'u'	0.3161	4.2767	0.0048	0.0000	4.5975
'ü'	0.1324	2.1939	0.0004	0.0000	2.3267
				Group:	51.0465

Table 5 exhibits the statistics for the syllables ending with the digrams 'al, ol, ul'. Similarly, Table 6 lists the frequencies for the syllables starting with the digrams 'la, lo, lu'. Table 7 gives the frequencies of the syllables starting with the letters 'k, g'. Table 8 shows the frequencies of the syllables ending with the digram 'at'. Table 9 presents the frequencies of the syllables starting with the digram 'na'. Table 10 shows the frequencies of the syllables ending with the digrams 'el, em, en'.

Table 5

Frequencies(%) of the syllables ending wıth the dıgrams 'al, ol, ul'

	1-letter	2-letter	3-letter	4-letter	Total
'al'	-	0.2504	0.5063	0.0023	0.7590
'ol'	-	0.4921	0.1486	0.0031	0.6439
'ul'	-	0.0009	0.2417	0.0000	0.2426
				Group:	1.6455

Table 6

Frequencies(%) of the syllables starting wıth the dıgrams 'la, lo, lu'

	1 letter	2 letters	3 letters	4 letter	Total
'la'	-	2.3886	1.4385	0.0038	3.8310
'lo'	-	0.0433	0.0228	0.0018	0.0679
'lu'	-	0.3219	0.2725	0.0001	0.5945
				Group:	4.4934

Table 7

Frequencies(%) of the syllables starting wıth the letters 'k, g'

	1-letter	2-letter	3-letter	4-letter	Total
'k'	-	3.7566	2.5156	0.1018	6.3739
'g'	-	1.8090	1.1707	0.0605	3.0403
				Group:	9.4142

Table 8

Frequencies (%) of the syllables ending wıth the dıgram 'at'

	1-letter	2-letter	3-letter	4-letter	Total
'at'	-	0.1024	0.3880	0.0004	0.4908

Table 9
Frequencies (%) of the syllables starting with the digram 'na'

	1-letter	2-letter	3-letter	4-letter	Total
'na'	-	0.9818	0.1906	0.0041	1.1765

Table 10
Frequencies (%) of the syllables ending with the digram 'el, em, en'

	1-letter	2-letter	3-letter	4-letter	Total
'el'	-	0.0832	0.4198	0.0047	0.5078
'em'	-	0.0224	0.2534	0.0008	0.2765
'en'	-	0.1005	1.9986	0.0085	2.1076
				Group:	2.8919

General observations about these statistics can be summarized as follows:

(i) As stated above, for pronunciation disambiguation, special attention shall be devoted to the 2-letter syllables ending with vowels, particularly the ones ending with `a`, `e` and `i`.

(ii) Since the 1-letter syllables have to be vowels, Tables 5 to 10 have zero entries for 1-letter column as expected. As seen in Fig. 3, 1-letter syllables constitute almost 6% of the whole set. Since we have 6 of 8 vowels in Table 4, we can conclude that 1-letter syllables belonging to this group also require special attention.

(iii) It is very rare that a 3- or 4-letter syllable ends with a vowel; which can also be observed from Table 4. Hence, such syllables might have small importance.

(iv) As seen from Table 6, 2- and 3-letter syllables starting with the digram `la` has considerable frequency.

(v) As seen from Table 7, 2- and 3-letter syllables starting with the letter k has considerable frequency. Such syllables starting with the letter g are also of importance.

4 Second Level Statistical Analysis and Results

In [36], it has been identified that there exist at least 154 exceptional syllables which cause pronunciation ambiguity in Turkish. In this chapter, we focus our attention to these syllables, and give the statistical results for the frequencies of these 154 exceptional syllables. Table 11 lists the frequencies of these syllables (sorted from the most frequent to the least). It can be seen that syllables ending with `a` and `i` dominate the top positions of the list. It can be seen that some syllables belonging to more than one class (i.e. the classes mentioned in Section 2.2); such as `la`, `ka` and `na` have a considerable occurrence rate.

Table 11
Frequencies (%) of the 154 exceptional syllables (sorted from the most frequent to the least)

syllable	frequency	syllable	frequency	syllable	frequency
la	2.3886	kal	0.1416	pen	0.0220
di	1.6241	ga	0.1336	dol	0.0213
da	1.6144	mü	0.1186	sem	0.0182
ya	1.5514	vi	0.1064	bol	0.0161
ka	1.4985	cu	0.1063	gar	0.0160
a	1.4813	ren	0.1055	kam	0.0157
ma	1.3836	sen	0.1034	tel	0.0156
ra	1.1818	at	0.1024	tem	0.0154
i	1.1519	kan	0.0963	kut	0.0152
ri	1.0545	şu	0.0958	kun	0.0140
na	0.9818	hi	0.0933	tal	0.0140
bi	0.9293	men	0.0894	dem	0.0136
ni	0.8790	kat	0.0825	lon	0.0128
ki	0.8440	fi	0.0788	ral	0.0126
me	0.8109	ber	0.0785	sol	0.0118
ba	0.8035	bul	0.0713	bal	0.0109
du	0.7943	laş	0.0689	gan	0.0108
lar	0.7902	lur	0.0676	kum	0.0101
li	0.7885	yen	0.0659	cen	0.0100
ta	0.7688	yal	0.0612	rem	0.0090
bu	0.7615	hal	0.0611	şal	0.0081
ha	0.7507	kul	0.0605	kem	0.0076
sa	0.6981	bel	0.0597	nal	0.0062
si	0.6532	lun	0.0575	pal	0.0062
ti	0.6227	luk	0.0556	rol	0.0058
te	0.6201	lat	0.0547	lut	0.0055
den	0.5437	sal	0.0542	kel	0.0047
mi	0.4742	nem	0.0528	las	0.0046
nu	0.4026	hat	0.0524	cer	0.0043
ca	0.3924	hem	0.0513	yem	0.0042
ken	0.3627	vu	0.0446	yel	0.0042
lan	0.3341	lo	0.0433	cel	0.0039
lu	0.3219	lah	0.0431	laç	0.0038
u	0.3161	hu	0.0428	gal	0.0033
za	0.3150	fen	0.0424	gul	0.0032
şa	0.2869	kah	0.0423	zal	0.0032

syllable	frequency	syllable	frequency	syllable	frequency
tu	0.2804	lak	0.0421	zem	0.0026
ku	0.2681	zu	0.0392	fel	0.0024
ça	0.2596	lam	0.0391	fal	0.0023
al	0.2504	mem	0.0385	çem	0.0021
kar	0.2488	pi	0.0379	cem	0.0021
ru	0.2429	lay	0.0378	bem	0.0020
pa	0.2215	zen	0.0366	pul	0.0019
su	0.1914	lum	0.0341	ul	0.0009
va	0.1869	mal	0.0338	gat	0.0008
ben	0.1858	dal	0.0307	fol	0.0008
tü	0.1755	mo	0.0288	tol	0.0007
mu	0.1733	kol	0.0266	lom	0.0005
fa	0.1701	val	0.0265	pol	0.0004
ci	0.1561	lup	0.0239	ja	0.0000
zi	0.1497	sul	0.0236		
ten	0.1431	rat	0.0230		

We performed another analysis in order to identify the coverage rate. In other words, we tried to identify how much pronunciation disambiguation capability would be achieved by adding the words with the most occurring syllables to the pronunciation lexicon. Here is what we obtained: The most occurring 12 syllables constitute 50% of occurrences of whole exceptional syllables; similarly 50 of them constitute 90%, and 100 of them constitute 99% of exceptional occurrences. This trend is illustrated in more detail in Fig. 4.

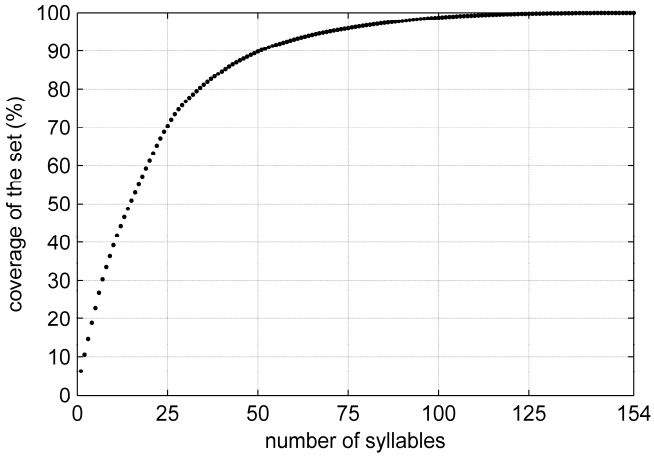

Figure 4
Percent ambiguity resolution coverage curve

We can rephrase the findings of this Section as follows: If a researcher wants to enrich his/her lexicon as defined in this study (Section 2.3), then he/she must start adding all words including the syllable `la`; and continue this process according to the order given in Table 11. The addition of all words having the first 50 syllables would give 90% pronunciation disambiguation capability, which seems to yield a more or less optimum efficiency (maximum coverage with minimal lexicon enrichment effort). The inclusion of the 100 most frequent exceptional syllables would imply 99% coverage, which means that the last 54 entries of Table 11 might be neglected practically.

Conclusions and Future Work

In this study, we have tried to identify the exceptional syllables for which the grapheme-to-phoneme mapping is not one-to-one, as well as the occurrence rates of these syllables. On the other hand, it should be noted that the given statistics refer to the total occurrences of these exceptional syllables (i.e. both the normal/default pronunciation and the abnormal/extraordinary pronunciation cases are counted together). For more granularity about the rate of extraordinary pronunciations, additional analyses are required; and for these analyses, the aforementioned pronunciation lexicon should be complete. Our near- and mid-term plans are to enrich the lexicon for the most occurring syllables, and try to come up with more statistics about such syllables (i.e. the rate of extraordinary pronunciation for these syllables).

In Table 12, the effectiveness of the proposed technique is demonstrated by means of some example sentences for which the pronunciation ambiguity for the existing exceptional syllables are resolved and the phonetic representations are obtained.

Table 12

Example sentences demonstrating the effectiveness of the proposed technique

Sample Text	**Relevant Proposed Phonetical Representation**
Tesislerden yararlanan tüm memurların, seyahatleri ve tatilleri esnasında bu hususa dikkat etmeleri gerektiği açıklandı.	Têsislerden yararlanan tüm mêmurların, seyahàtleri ve tâtilleri esnâsında bu husûsa dikkàt etmeleri gerektiği açıklandı.
Afet bölgesini beraberindeki heyetle ziyaret eden Hakkari Valisi, kabul ettiği felaketzedelere bugüne kadar sükunet ve fedakarlıkla göğüs gerdikleri problemlerin derhal giderileceğini, bu konuda hiç bir ihmalkarlığa tahammül edilmeyeceğini bildirdi.	Âfet bölgesini berâberindeki heyetle ziyâret eden Hakkãri Vâlisi, kabùl ettiği felãketzedelere bugüne kadar sükýnet ve fedâkârlıkla göğüs gerdikleri problemlerin derhàl giderileceğini, bu konuda hiç bir ihmàlkârlığa tahammül edilmeyeceğini bildirdi.
Zamanında belediyeye bağlı Zabıta Amirliği tarafından düzenlenmekte olan mahalli lale festivalinin, bu yıl Yeşil Vadi olarak da bilinen bölgede Kağıt Fabrikası'nın karşısındaki alanda valilik tarafından düzenleneceği bildirildi.	Zamânında belediyeye bağlı Zâbıta Âmirliği tarafından düzenlenmekte olan mahàllî lâle festivàlinin, bu yıl Yeşil Vâdi olarak da bilinen bölgede Kâğıt Fabrikası'nın karşısındaki alanda vâlilik tarafından düzenleneceği bildirildi.

Tüm sözlü ikazlara ve yazılı belgelere rağmen, Nisan-Haziran döneminde İran sınırı üzerinden gerçekleşen anormal mülteci akımına karşı acil bir önlem alınmadı.	Tüm sözlü îkazlara ve yazılı bëlgelere rağmen, Nîsan-Hazîran döneminde Îran sınırı üzerinden gerçekleşen anormàl mültecî akımına karşı âcil bir önlem alınmadı.
Cesaretleri ile nam salmış olan Cezayir korsanları, rutubetten kaynaklı suhulet düşüklüğü nedeniyle, kalyonlarının seyrini normalden daha düşük süratle, narin ve nazik bir şekilde idame ettiriyorlardı.	Cesâretleri ile nam salmış olan Cezâyir korsanları, rutûbetten kaynaklı suhûlet düşüklüğü nedeniyle, kàlyonlarının seyrini normàlden daha düşük süràtle, nârin ve nâzik bir şekilde idâme ettiriyorlardı.

The results showed that among the exceptional syllables, especially for the 1-letter and 2-letter syllables ending with the letters `a`, `e` and `i`, are the most frequent ones generally. At this point, we make the following remarks based on our personal experiences: Even though the syllables ending with `e` are very frequent, the phenomenon of lengthening the vowel `e` is very rare. In other words, there are only a limited number of words (in the order of a couple) for which the vowel `e` is pronounced in lengthened form (such as `memur` (government officer), represented and pronounced as `mêmur`; `tesis` (facility), represented and pronounced as `têsis`; `temin` (obtainment), represented and pronounced as `têmin`). Hence, for the syllables ending with the letter `e`, it is very easy to complete the pronunciation lexicon. On the other hand, there are numerous words for which the vowel `a` is pronounced in lengthened form (in the order of thousands) and for which the vowel `i` is pronounced in lengthened form (in the order of hundreds). Hence, it will be a time- and effort-consuming task to identify all such words and include them in the lexicon. In addition, due to their being elements of multiple classes, syllables `la` and `ka` (and the words including them) are very frequent, and they also require attention.

An important point to be emphasized is that the proposed method is not able to resolve ambiguities despite its ability to detect them for the homeomorphic/isographic words (e.g. `kar` (snow/profit), `ama` (but/blind), `adet` (number/habit), etc.). As stated earlier in Section 2.3, syntactic analysis (moreover, in some instances, even contextual meaning analysis) is required for the resolution of ambiguities caused by the homeomorphic/isographic words. On the other hand, another analysis is also performed in order to have a qualitative idea about the occurrence rate of such words in meaningful Turkish texts. As seen in Table 13, frequencies of such words are computed as negligible for a test performed by using a text of 1,549,647 words. Hence, it can be concluded that the coverage of the proposed technique is quite good considering its practicality.

At this point, the following remark shall be made in order to prevent any misinterpretations of the results given in Table 13. The numbers given in Table 13 indicate the number of words starting with the relevant pattern. For example, the number 12,752 for the pattern `kar` means that 12,752 words starting with the syllable `kar` were encountered in the text; accounting not only the isolated homemomorphic word `kar` (snow or profit) but also the words such as `karşı`

(against), karşıt (opposite), kartal (eagle), karton (cartoon), karmaşık (complicated), etc. together with their all suffixed forms. The proposed method already resolves all the pronunciation ambiguities for the words karşı, karşıt, kartal, karmaşık, etc. and all their suffixed forms; but only gets stuck for the occurences of kar and its suffixed forms (which is only a very limited percent of the number 12,752). For the occurrences of kar and its suffixed forms, the proposed methods leave them as is (i.e. all the occurrences are to be pronounced as if the word means snow); hence, the occurrences of kar with the meaning profit will be misrepresented and mispronounced, and certainly these constitute a much lower percentage of the number 12,752. The same arguments are valid also for the other homeomorphic words seen in Table 13. Considering this, the percentage of misrepresentations and mispronunciations with the proposed method are quite low (i.e. the total number seen in Table 13 is a very exaggerated upper bound; the number of the exact misrepresentations and mispronunciations would probably be much less than 1/10 of the total number given in Table 13).

Table 13
Frequencies of the homeomorphic/isographic words

Word	Pronunciation and Meaning	Pronunciation and Meaning	Occurance
adet	adet (number)	âdet (habit)	355
ala	ala (colorful)	âlã (superb)	2619
ali	ali (a proper name)	âlî (lofty)	936
ama	ama (but)	âmâ (blind)	7504
aşık	aşık (compete)	âşık (lover)	411
atıl	atıl (pounce)	âtıl (idle)	424
dahi	dahî (even)	dâhi (genius)	393
hala	hala (aunt)	hâlã (still)	959
kar	kar (snow)	kár (profit)	12752
mal	mal (goods)	màl (cost)	908
sol	sol (left)	sòl (note G)	1032
usul	usul (quitely)	usùl (method)	197
varis	varis (varicosis)	vâris (inheritor)	6
		Total	28496

To our belief, the results of this study might additionally serve as a guideline for researches related with different topics:

(i) General syllable statistics might find application areas such as statistical ambiguity resolution in optical character recognition, or even in speech recognition.

(ii) These statistics might also be considered for the computation of syllable-based entropy calculation of the Turkish language. Such an entropy value might be used in information theoretical research studies.

(iii) The syllables, their frequencies and their lengths might also provide input for the definition of new readability metrics of Turkish texts.

Moreover, even though the statistical data provided here are focused in Turkish, our approach might also be applied to another language in future studies for similar purposes.

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Optimization Methods of EWMA Statistics

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Abstract: Many intrusions which attempt to compromise the security of computer and network systems manifest themselves in changes in the intensity of events. Because of the ability of exponentially weighted moving average (EWMA) statistics to monitor the rate of occurrences of events based on their intensity, this technique is appropriate for implementation in control limits based algorithms. The research has shown that the usual application of this algorithm on computer network traffic, as applied in industrial processes, does not provide acceptable results. The paper also gives a review of possible optimization methods.

Keywords: intrusion detection; EWMA; control limits; optimization; autocorrelation; ARL

1 Introduction

The exponentially weighted moving average is a statistic for monitoring the process that averages the data in a way that gives less and less weight to data as they are further removed in time. For the EWMA control technique, the decision regarding the state of control of the process depends on the EWMA statistic, which is an exponentially weighted average of all prior data, including the most recent measurements.

By the choice of weighting factor λ, the EWMA control procedure can be made sensitive to a small or gradual drift in the process.

The statistic that is calculated is the following:

$$EWMA_t = \lambda\, Y_t + (1-\lambda)\, EWMA_{t-1} \quad \text{for } t = 1, 2, \ldots, n \tag{1}$$

where

- $EWMA_0$ is the mean of historical data

- Y_t is the observation at time t
- n is the number of observations to be monitored including $EWMA_0$
- $0 < \lambda \leq 1$ is a constant that determines the depth of memory.

This equation was established by Roberts as described in [4].

The parameter λ determines the rate at which "older" data enter into the calculation of the EWMA statistic. A value of $\lambda = 1$ implies that only the most recent measurement influences the EWMA. Thus, a large value of $\lambda = 1$ gives more weight to recent data and less weight to older data; a small value of λ gives more weight to older data. The value of λ is usually set between 0.2 and 0.3 [2], although this choice is somewhat arbitrary. Lucas and Saccucci [3] have shown that although the smoothing factor λ used in an EWMA chart is usually recommended to be in the interval between 0.05 to 0.25, in practice the optimally designed smoothing factor depends not only on the given size of the mean shift δ, but also on a given in-control Average Run Length (ARL). ARL represents the average number of determined process points before the first point indices the appearance of out-of-control state (exceeding one of the control limits).

The estimated variance of the EWMA statistic is approximately:

$$\sigma^2_{EWMA} = (\lambda / (2 - \lambda))\ \sigma^2 \tag{2}$$

where σ is the standard deviation calculated from the historical data.

The center line for the control chart is the target value or $EWMA_0$. The upper and lower control limits are:

$$UCL = EWMA_0 + k\sigma_{EWMA} \tag{3}$$

$$LCL = EWMA_0 - k\sigma_{EWMA} \tag{4}$$

where the factor k is either set equal to 3 (the 3-sigma control limits) or chosen using the Lucas and Saccucci tables (ARL = 370).

In addition to the aforementioned authors, the publications [6] - [13] and [19] have also dealt with the topic of EWMA statistics and statistical anomaly detection in computer networks.

Control charts are specialized time series plots which assist in determining whether a process is in statistical control. Some of the most widely used forms of control charts are X-R charts and Individuals charts. These are frequently referred to as "Shewhart" charts after the control charting pioneer, Walter Shewhart, who introduced such techniques. These charts are sensitive to detecting relatively large shifts in the process (i.e. of the order of 1.5σ or above). In computer network practice, shifts can be caused by intrusion or attack, for example. Two types of charts are usually used to detect smaller shifts (less than 1.5σ), namely cumulative sum (or CUSUM) charts and EWMA charts. A CUSUM chart plots the cumulative sums of the deviations of each sample value from a target value. An

alternative technique to detect small shifts is to use the EWMA methodology. This type of chart has some very attractive properties, in particular:

1 Unlike X-R and Individuals charts, all of the data collected over time may be used to determine the control status of a process.

2 Like the CUSUM, the EWMA utilizes all previous observations, but the weight attached to data exponentially decreases as the observations become older and older.

3 The EWMA is often superior to the CUSUM charting technique due to the fact that it detects larger shifts better.

4 EWMA schemes may be applied for monitoring standard deviations in addition to the process mean.

5 EWMA schemes can be used to forecast values of a process mean.

6 The EWMA methodology is not sensitive to normality assumptions.

In real situations, the exact value of the shift size is often unknown and can only be reasonably assumed to vary within a certain range. Such a range of shifts deteriorates the performance of existing control charts. One of the algorithms for determining the maximal shift in normal traffic is described in [16].

The paper describes the process of the application of the EWMA algorithm for one major user, given as an example. It can be shown that the obtained results are valid for the other analyzed users as well. This research uses samples of authentic network traffic (i.e. traffic intensity in a unit of time). Traffic analysis is realized in the form of statistical calculations on samples which derive from the traffic curve. From the appropriate pattern of Internet traffic, 35 samples of local maximums are taken in order to ensure that the statistical analysis is performed on a large sample (number of samples $n > 30$), thus supporting and leading to general conclusions.

The aim of this research is to determine those allowed EWMA values of traffic, so that when they are exceeded, it will be considered as the appearance of a statistical anomaly suspected to attack. In this sense, the choice of only local maximums for analysis can be accepted as logical, because the critical point of maximum value of aggregate traffic is in this way also included.

The proposed method of calculating the overall optimal value Λ is applied to traffic patterns, on the basis of which the lower and upper control limits of traffic are determined. For statistical detection of an attack, the primary interest is the appearance of a situation in which the upper control limit is exceeded. The overstepping of the lower control limit can be understood as a statistical anomaly, but in the case of this research, it is only related to the local maximum (and not to the aggregate network traffic) and as such does not endanger the security of the computer network in general. Therefore, the situation in which the value of

network traffic falls below some lower limit is not considered to be a suspicious event or attack, because the initial presumption of this research is the increase of traffic during an external attack. For the observed pattern of traffic, EWMA values are calculated and if these values are outside of the control limits, that situation is interpreted as a statistical anomaly. Emphasis in this work is placed on determining the occurrence of false alarms, as an important security feature of the applied algorithm.

2 Optimized Exponential Smoothing

Calculating the optimal value of parameter λ is based on the study of authentic samples of network traffic. Random variations of network traffic are normal phenomena in the observed sample. In order to decrease or eliminate the influence of individual random variations of network traffic on occurrence of false alarms, the procedure of exponential smoothing is applied, as an aspect of data preprocessing.

For any time period t, the smoothed value S_t is determined by computing:

$$S_t = \lambda\, y_{t-1} + (1 - \lambda)\, S_{t-1} \quad \text{where } 0 < \lambda \leq 1 \text{ and } t \geq 3 \tag{5}$$

This is the basic equation of exponential smoothing. The formulation here is given by Hunter [2]. It should be noted that there is an alternative approach, in which, according to Roberts [4], y_t is used instead of y_{t-1}.

This smoothing scheme starts by setting S_2 to y_1 (there is no S_1), where S_i stands for smoothed observation or EWMA, and y_i stands for the original observation. The subscripts refer to the time periods 1, 2, ..., n. For example, the third period is $S_3 = \lambda\, y_2 + (1 - \lambda)\, S_2$ and so on.

There is no generally accepted statistical procedure for choosing λ. In that situation, the method of least squares might be adequate to determine the optimal value of λ for which the sum of the squared errors (SSE) $(S_{n-1} - y_{n-1})^2$ is minimized.

The method of least squares represents a standard approach to the approximate solution of over-determined systems (i.e. sets of equations in which there are more equations than unknowns). The most important application is in data fitting. The best fit in the least squares sense minimizes the sum of squared residuals, a residual being the difference between an observed value and the fitted value provided by a model.

Here is an illustration of this principle through an example. Consider the following data set consisting of n observations of data flow over time – for starting $\lambda = 0.1$:

Table 1
Smoothing scheme

Time	Flow (y_t)	S_t	Error ($S_t - y_t$)	Error squared
1	y_1			
2	y_2	y_1	E_2	E_{22}
3	y_3	S_3	E_3	E_{32}
...	...	...	...	...
n	y_n	S_n	E_n	E_{n2}
				SSE_n

The sum of the squared errors (SSE) is then $SSE_{0.1}$. After that, the SSE is calculated for $\lambda = 0.2$. If $SSE_{0.2} < SSE_{0.1}$ then $SSE_{0.2}$ is better value for λ. This iterative procedure is related to the range of λ between 0.1 and 0.9. In this way, the best initial choice for λ is determined and then, for getting more precise value, search optionally continues between $\lambda-\Delta\lambda$ and $\lambda+\Delta\lambda$, where $\Delta\lambda$ is an arbitrarily small interval around λ (for instance, in practical applications, ± 10% around optimal λ).

Table 2
Comparison of smoothing schemes

time	y_t	EWMA	S_t
1	52,00	50,60	
2	47,00	49,52	52,00
3	53,00	50,56	50,50
4	49,30	50,18	51,25
5	50,10	50,16	50,67
6	47,00	49,21	50,50
7	51,00	49,75	49,45
8	50,10	49,85	49,91
9	51,20	50,26	49,97
10	50,50	50,33	50,34
11	49,60	50,11	50,39
12	47,60	49,36	50,15
13	49,90	49,52	49,39
14	51,30	50,05	49,54
15	47,80	49,38	50,07
16	51,20	49,92	49,39
17	52,60	50,73	49,93
18	52,40	51,23	50,73
19	53,60	51,94	51,23
20	52,10	51,99	51,94
			51,99

Comparative analysis of two different approaches (Roberts and Hunter) can be shown using the example of a process (y_t), with adopted values $EWMA_0 = 50$ and $\lambda = 0.3$. EWMA values in the table below correspond to Roberts's and S_t to Hunter's equation.

In Table 2 the fields with approximately equal values are marked with a lighter color, while fields with equal values are marked with a darker color. From this analysis it can be concluded that after a certain number of samples (in this case about the 16th sample) both schemes give the same smoothed values.

The behavior of both smoothing schemes will be examined also with SSE values. After calculating SSE for different λ, results were as follows:

Table 3

Comparison of values for SSE according to Roberts and Hunter

λ	SSE (Roberts)	SSE (Hunter)
0.1	62.81	75.01
0.2	49.95	55.86
0.3	39.28	42.16
0.4	30.25	31.62
0.5	22.40	23.01
0.6	15.50	15.71
0.7	9.55	9.57
0.8	4.70	4.66
0.9	1.31	1.29

Analysis of the obtained results has shown that approximately similar values were obtained, with greater coincidence at higher values of smoothing factor.

The initial EWMA plays an important role in computing all the subsequent EWMA's. There are several approaches to define this value:

1) Setting S_2 to y_1
2) Setting S_2 to the target of the process
3) Setting S_2 to average of the first four or five observations

It can also be shown that the smaller the value of λ, the more important is the selection of the initial EWMA. The user would be well-advised to try several methods before finalizing the settings.

For different input values of initial parameter S_2, an application in "Matlab" is created which calculates and plots the dependence of SSE and partial value of λ in range of $0 \div 1$, with adjustable step. In addition, the optimal value λ_{opt} is also calculated. For the optimal value, in accordance with the smoothing scheme, that particular value is taken for which the SSE is minimal. The following figure shows an example for calculating the optimal value of the parameter λ for a specific S_2.

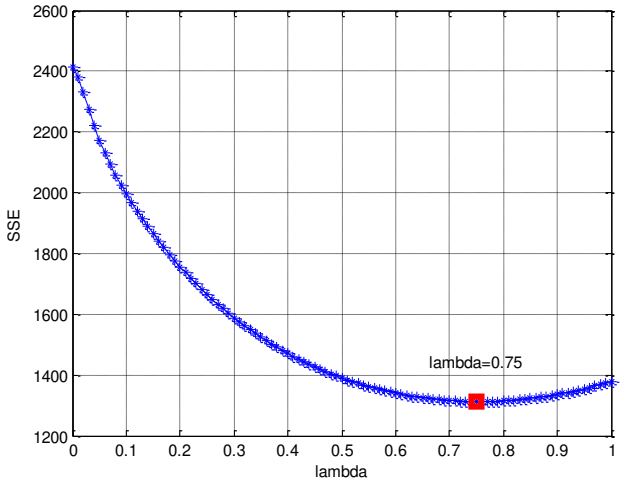

Figure 1
Calculation of λ_{opt}(SSE)

Due to the lack of an exact method of calculation in available publications about the determination of the initial S_2 in the procedure of exponential smoothing, the authors of this paper have dealt with researching the link between selection of $S_2 = y_1$ and λ_{opt}, i.e. $S_2(\lambda_{opt})$. In that sense, the range of S_2 is determined using the lowest to the highest sample value during the period of observation. This research was conducted on an authentic sample of network traffic of an Internet service provider and the segment of observation was the range of values of local maximums (in this concrete case $S_2 = 8 \div 34$ Mb/s), with a large enough number of values, taking into account the generality of conclusions. The period of observation was one month. The next table shows the numerical and graphical dependence $S_2(\lambda_{opt})$.

Since a set of different results has been obtained for partial values of λ_{opt}, in order to determine the overall optimal parameter Λ_{opt}, the measures of central tendency will be examined. There are three most common measures of central tendency:

- Average - the arithmetic mean, calculated by adding a group of numbers and then dividing by the count of those numbers.
- Median - the middle number of a group of numbers; that is, half the numbers have values that are greater than the median, and half the numbers have values that are less than the median.
- Mode - the most frequently occurring number in a group of numbers.

For a symmetrical distribution of a group of numbers, these three measures of central tendency are all the same. For a skewed distribution of a group of numbers, they can be different.

Table 4
Calculation of $S_2(\lambda_{opt})$

	S_2	λ_{opt}
1	8	0,72
2	9	0,72
3	10	0,72
4	11	0,72
5	12	0,71
6	13	0,71
7	14	0,72
8	15	0,72
9	16	0,72
10	17	0,72
11	18	0,72
12	18,5	0,73
13	19	0,73
14	19,5	0,73
15	20	0,73
16	20,5	0,73
17	21	0,74
18	21,5	0,74
19	22	0,74
20	22,5	0,75
21	23	0,75
22	23,5	0,75
23	24	0,75
24	25	0,76
25	26	0,77
26	27	0,77
27	28	0,78
28	29	0,79
29	30	0,8
30	31	0,8
31	32	0,81
32	33	0,82
33	34	0,82

In this particular case the following values are calculated (according to the previous table): average = 0.7482, median = 0.74 and mode = 0.72. Since the values for average and median do not differ significantly, the authors suggest for the overall optimal parameter Λ_{opt} to accept the average of all the partial results. In this particular case it is approximately 0.75, which significantly differs from the usually suggested values (between 0.2 and 0.3).

3 ARL Curves

Using a graphical method, the EWMA chart can be designed to have minimal ARL for the out-of-control situation, for the known shift of the mean δ and given ARL for the in-control situation. This chart has two parameters - λ and k (derives from the definition of control limits).

The figures below show the dependence of λ and k of the mean shift δ, for ARL as parameter. Using appropriate curves, values k = 2.7878 and λ = 0.1417 were determined as the optimal choice for the earliest detection of shift δ = 1σ.

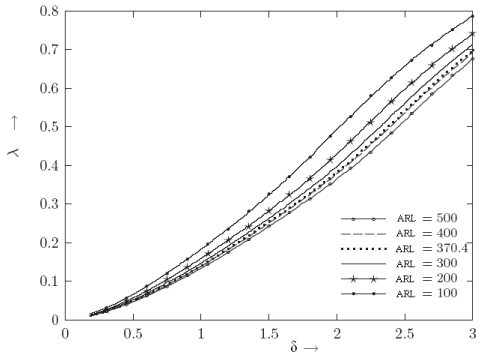

Figure 2

Optimal choice of *λ* in function of the mean shift [18]

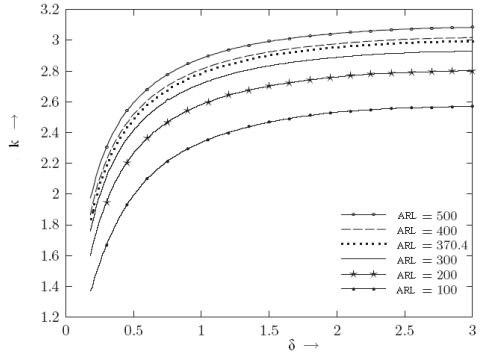

Figure 3

Optimal choice of *k* in function of the mean shift [18]

4 Autocorrelation

Autocorrelation or serial correlation of a time series means that the value of the observed variable in a time unit depends on values which appear prior to or later in the series. In practical situations, autocorrelation of the first order is usually examined, which may be shown by a simple correlation coefficient or so-called autocorrelation coefficient. Let R_t be the time series data, where t = 1, 2, ...,T, then the autocorrelation coefficient of the first order is given by:

$$\rho(R) = \frac{\sum_{t=2}^{T} R_t \cdot R_{t-1}}{\sqrt{\sum_{t=2}^{T} R_t^2 \cdot \sum_{t=2}^{T} R_{t-1}^2}}, \; -1 \leq \rho \leq 1 \tag{6}$$

One of the standard features of traffic time series is that the increasing rates of traffic R_t are not mutually significantly autocorrelated, i.e. the value of the autocorrelation coefficient is near zero. At the same time, this means that the distribution of positive and negative values of increasing rates is random and that does not follow a specific systematic regularity. Positive autocorrelation implies that the positive values are followed by mainly positive values and negative values by negative ones and then $\rho \approx +1$. In the case of negative autocorrelation, there is often a change of sign, i.e. the positive rate in most cases leads to a negative rate and vice versa and then $\rho \approx -1$. Since there is no typical scheme, on the basis of the positive rate in one particular time period there is no way of concluding (it cannot be concluded) with a significant probability that in the next period either a growth or decline will appear. The same applies to the situation for the negative rate.

Researchers in [5] dealt with the influence of autocorrelated and uncorrelated data on the behavior of an intrusion detection algorithm. In their work they came to conclusion that the EWMA algorithm for autocorrelated and uncorrelated data works well in the sense of intrusion detection in some information systems. The advantage of the EWMA technique for uncorrelated data is that this technique (as opposed to the case of the autocorrelated data) can detect not only rapid changes in the intensity of events, but also small changes in the mean value realized through the gradual increase or decrease of the intensity of events. However, in EWMA for uncorrelated data, the initial value of smoothed intensity events is to be reset after intrusion detection, in order to avoid the impact of current values of parameters on future results (*carry-over effect*). In the case of EWMA for autocorrelated data this reset is not necessary, because EWMA automatically adjusts the upper and lower control limits. Generally, the smoothing constant should not be too small, so that a short-term trend in the intensity of events in the recent past can be detected. Other publications have also shown the need for taking into account the autocorrelation of input data. As is emphasized in [17], in the case of dynamic systems the autocorrelation in variables is taking into account incorporating time lags of the time series during the modeling stage.

The samples of network traffic were obtained by the network software “MRTG“ (Multi Router Traffic Grapher). This software generates three types of graphs:

- Daily – with the calculation of a 5-minute average
- Weekly – with the calculation of a 30-minute average
- Monthly – with the calculation of a 2-hour average

The graphs also enable numerical information on the maximum and average traffic for the appropriate period of time.

Daily, weekly and monthly graphs of the first measurement will be used for the calculation of the initial historical data, while the application of EWMA statistics, with the aim of checking the validity of certain parameters, will be realized on daily, weekly and monthly traffic graphs of the second measurement.

For the application of exponential smoothing method to the network traffic, it is necessary to first determine the historical values: $EWMA_0$ and standard deviation σ_0. For this purpose, it is necessary to collect appropriate traffic samples to perform adequate calculations. This study will use a total of 105 samples of local maximum: 35 samples from the daily traffic graph, 35 samples from the weekly traffic graph and 35 samples from the monthly traffic graph.

On the basis of the data presented in the given table the following can be calculated: $EWMA_0 = 23.10$ and $\sigma_0 = 4.87$.

In accordance with the method described above, and to justify the usage of EWMA statistics, it is important to determine the statistical independence of the samples, which will be examined by checking the existence of correlation between data. For this purpose, Pearson's correlation coefficient will be used, which is supplied as a ratio of covariances of two variables and the product of their standard deviations:

$$\rho_{xy} = Cov\,(X,Y) / (\sigma_x \cdot \sigma_y) \qquad -1 \leq \rho_{xy} \leq 1 \tag{7}$$

Other authors have proposed different interpretations of ways of correlation coefficient. Cohen [1] noted that all the criteria are based on a greater or lesser extent of arbitrariness and should not be kept too strictly. Yet, one often-used interpretation of these coefficients is given below, as described in [15]:

- ρ between 0 and 0.2 – no correlation or it is insignificant
- ρ between 0.2 and 0.4 – low correlation
- ρ between 0.4 and 0.6 – moderate correlation
- ρ between 0.6 and 0.8 – significant correlation
- ρ between 0.8 and 1 – high correlation

Table 5
Network samples

Time	y_t(daily)	y_t(weekly)	y_t(monthly)
1	12	21	23
2	10.5	22.5	30
3	8.5	23	27
4	10.5	20	27
5	18	20.5	25
6	22	23.5	27
7	25.5	24	22
8	20	21	24
9	33.9	23	23
10	25	25	20
11	24	25.5	24.5
12	26.5	24.5	26.5
13	27.5	22	28
14	23	25.5	27
15	25	27	23
16	24	28	22.5
17	23	27	26.5
18	23	28	31
19	22	25.5	22.5
20	23	30	22.5
21	23	29	27
22	23	26.5	25
23	23	29	26
24	16	26.5	28
25	16	27.5	21
26	9	26	24
27	11.5	25	22
28	8.5	24	22
29	8.5	23.5	22
30	14	22	23
31	23	22.5	27
32	23	24	29
33	20	24	25
34	23	25	25
35	23	23	22

The value of correlation coefficient ρ_{xy} can be calculated using the statistical function CORREL (array1, array2) in MS Excel. When examining the table above, it is possible to identify three series of data (daily, weekly and monthly) and in this sense three different correlation coefficients can be calculated:

- correlation coefficient for daily – weekly series: $\rho_1 = 0.28 \rightarrow$ low correlation
- correlation coefficient for daily – monthly series: $\rho_2 = 0.04$
- correlation coefficient for weekly – monthly series: $\rho_3 = -0.04$

Besides testing the correlation coefficient within a single measurement, it is important to check the existence of correlation between corresponding periods

from different measurements. For that purpose, values of correlation coefficient of two daily (weekly, monthly) intervals are checked and the following results are obtained:

- correlation coefficient for daily – daily series: $\rho_4 = -0.15$
- correlation coefficient for weekly – weekly series: $\rho_5 = 0.11$
- correlation coefficient for monthly – monthly series: $\rho_6 = -0.02$

As all calculated coefficients are with low degree of correlation, or without it, it can be concluded that the used data are statistically independent and that the application of EWMA statistics is justified.

5 Illustration of Results

The influence of the appropriate lambda value is illustrated by the following figure. Based on samples of authentic network traffic (daily traffic), a set of correspondent EWMA values are calculated. The curve in the first diagram was obtained for the optimized value of lambda (in this case, $\lambda = 0.91$), while the second diagram relates to the often proposed value of 0.25.

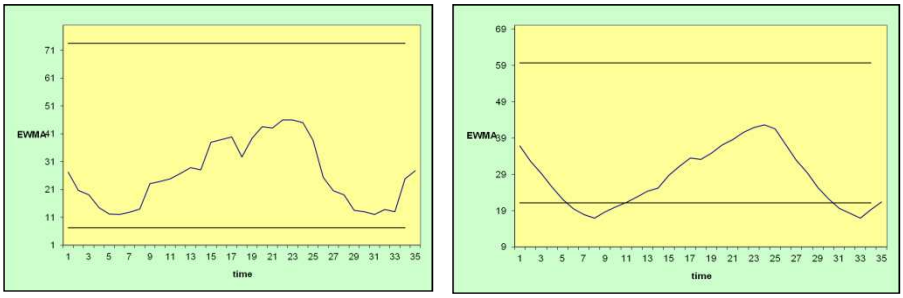

Figure 4
The effect of optimization

It is important to emphasize the multiple exceeding of the lower control limit in the second diagram, which represents a situation of statistical anomaly causing false alarms.

Conclusions

The aim of this research was to examine the possibility of applying EWMA statistics in intrusion detection in network traffic.

The research has shown that direct application of this algorithm on computer network traffic, as applied in industrial processes, does not provide acceptable results. Namely, often proposed values for exponential smoothing factor in case of

network application of the algorithm, may in some circumstances lead to the creation of false alarms, thus endangering the security level of the system. Due to the lack of an acceptable precise method for the determination of the initial value of the coefficient in exponential smoothing procedure in available publications, this research has been directed towards establishing a relation between the choice of initial ratio and optimal value for smoothing. By creating the appropriate application, the practical way was presented for testing the impact of different values of parameters on the level of anomaly detection. This enabled the establishment of graphical presentation of input depending on output sizes, which all contributed to the creation of the proposed method for calculating the optimal value of smoothing factor.

Before the start of the implementation of statistical analysis of traffic, the extent of autocorrelation between the used data must be examined, by calculating the correlation coefficients. One of the important results is that it is shown that analysis of network traffic properties based on individual patterns of daily traffic exclusively is not recommended, because of the increased level of autocorrelation. For this reason, when calculating the historical parameters, network traffic must be viewed in a wider context of time, taking into account the weekly and monthly periods. Using the network monitoring software, it is also necessary to determine the maximum variations of basic traffic characteristics (average and maximum).

To make this algorithm properly applicable in the network environment, it is necessary to perform previous processing of historical data, in order to obtain initial values of key parameters.

Based on the proof lent by the obtained results it can be concluded that the choice of EWMA parameters significantly affects the operation of this algorithm in a network environment. Therefore, the optimization process of parameters before the application of the algorithm is of particular importance.

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A New, Tensile Test-based Parameter Identification Method for Large-Strain Generalized Maxwell-Model

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Abstract: Parameter identification methods available in the literature are based on complex and time-consuming experiments, such as dynamic-mechanical-thermal-analysis (DMTA), stress relaxation tests, etc. To the authors' best knowledge there is no method in the literature which would be able to identify large-strain viscoelastic parameters of generalized Maxwell-model from simple constant strain rate tensile tests. In this paper, the authors present a new method which is based on two tensile tests performed at different strain rates. Firstly, a series of experiments (tensile tests, stress relaxation tests) is carried out on standard isoprene rubber specimens and then analytical calculations as well as finite element simulations on the basis of identified material parameters are performed. These computations prove the applicability of the method. Although the proposed method is presented for uniaxial tension, it is fully applicable to other load types, such as biaxial tension, simple shear, and planar shear. Additionally, it can be generalized for other spring-dashpot models.

Keywords: viscoelasticity; parameter identification; tensile test; rubber; finite element analysis

1 Introduction

In general usage, the term elastomer means a group of polymers characterized by large deformability, time-dependent (viscoelastic) behaviour and considerable changes in material behaviour by temperature. Further properties of elastomers include a stress-strain curve demonstrating strongly strain-rate dependent non-linear characteristics and incompressibility, making it really difficult for engineers to determine the dimensions of structural components made of them. In spite of innumerable problems, many structural components made of elastomers are applied in the automobile industry, as the special capabilities of this class of

materials can be exploited extremely well. Elastomers are obviously predominant in vehicle tires, seals of mechanical equipment, door sealings or windscreen wipers.

The complex mechanical behaviour of elastomers can be traced back to three clearly discernible effects which appear together in real rubber applications. These include non-linear behaviour in the case of large strains; finite viscoelastic behaviour; and softening, coupled with the rearrangement of molecule chains in the material (Mullins effect).

Over the last 50 years, numerous hyperelastic models have been developed to model the behaviour of rubber-like materials. Some of these material laws describe the non-linear characteristic of stress–strain curve using invariants of the Cauchy-Green's tensor, while other approaches apply more complex models based on molecular structure. Both approaches apply constants depending on material type and test conditions [1, 2].

In addition to taking non-linear behaviour into consideration, it is also possible to consider the dependence on the excitation frequency or strain rate. In many cases, the so-called Standard-Solid model – or its extended version, the generalized Maxwell-model – is used for modeling the time-dependent behaviour of rubber-like materials.

The latter describes stress relaxation not only qualitatively but also quantitatively and is available as a built in material model in most commercial finite element (FE) software packages (MSC. Marc, Abaqus, Ansys, etc). In most cases the viscoelastic material behaviour is characterized by dynamic-mechanical-thermal analysis (DMTA), or stress relaxation tests using the time-temperature superposition principle. However, it must be mentioned that torsional rheometry is also widely used for the characterization of plastics. In [3], DMTA tests are performed in order to identify the viscoelastic material parameters of a generalized Maxwell model. To characterize the strain dependency of the material, DMTA tests carried out at different strain levels can be used as presented in [4]. [5, 6] show examples for the application of generalized Maxwell-model in FE contact simulations. Viscoelastic properties of the rheological model were determined by DMTA measurements in both cases. The parameters of the rheological model can also be determined by stress relaxation tests, as presented in [7 and 8]. Finally, [9] shows how the viscoelastic properties of different spring-dashpot models can be determined by experiments with torsional rheometer.

In addition to the above, rubber behaviour is characterized by considerable softening as a consequence of repeated loading. During the loading cycles, disordered polymer chains in the material become partly ordered, thus reducing the force required for their deformation. Chain arrangement occurs characteristically under the first few load cycles; further important changes cannot be detected afterwards.

Linear viscoelasticity is properly described in the literature. However, the question arises of how to take into consideration the large strain, non-linear and time-dependent behaviour of the material simultaneously. Whilst this field of material science is extremely important for engineers dealing with the design of rubber components, it is very difficult to find application-oriented studies where the theory is described in an easy to understand manner.

In this paper, the authors present a new, tensile test-based parameter identification method for large-strain generalized Maxwell-model. Parameters are identified on the basis of two tensile tests of different strain rates and tested by FE and analytical calculations. The advantage of the proposed method is discussed in comparison with the results of a stress relaxation-based parameter identification technique.

2 Experimental Background

In order to test the methods examined, uniaxial tensile tests and stress relaxation tests were performed on a standard (ISO 527-3:1996) specimen cut out of an isoprene rubber (IR) plate. Tests were performed at the laboratory of the Department of Polymer Engineering at Budapest University of Technology and Economics (BME), on a Zwick Z005 type tensile tester. Table 1 shows the main parameters of the material tested.

Table 1
Main parameters of the tested Isoprene rubber

Elastomer base	Density [g/cm^3]	Shore A hardness	Temperature range [^{o}C]	Min. tensile strength [MPa]	Min. elongation at brake [%]
IR	1.5	60	-30 - +60	4	180

The specimen had a nominal length of l_0 = 60 mm, width of a_0 = 8 mm and thickness of b_0 = 10 mm. The standard deviation of specimen dimensions did not exceed 5% of the nominal dimensions.

In order to examine the Mullins effect, the fixed specimen was loaded at a speed of 100 mm/min at four consecutive times until 100% strain level. Engineering stress (σ^m)-strain (ε^m) curves were calculated from measured force (F) - elongation (Δl) data using Eqs. (1) and (2). Figure 1 shows the engineering stress-strain curves.

$$\varepsilon^m = \frac{\Delta l}{l_0} \tag{1}$$

$$\sigma^m = \frac{F}{A_0} = \frac{F}{a_0 \cdot b_0} \tag{2}$$

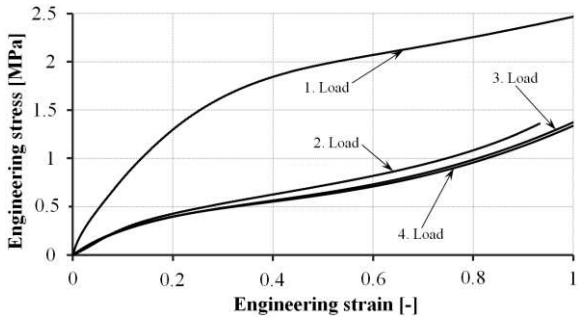


Figure 1

Softening of rubber specimens in the course of four consecutive loadings

The measurement results properly illustrate the so-called Mullins effect consequent upon the arrangement of polymer chains in filled rubbers. After the first loading, there is a significant change in the characteristic and the values of the curves, while the change after the third loading does not exceed 1%.

In addition to cyclic constant strain rate tensile tests, measurements were performed to examine the impact of strain rate on the stress-strain curve. During the test, specimens were loaded at a constant speed up to 100% strain level. Figure 2 shows the engineering stress-strain curves derived from the measured force-elongation curves by Eq. (1) and (2) at speeds of 1000, 500, 100 and 10 mm/min, corresponding to the strain rate of 0.27, 0.138, 0.027 and 0.00277 1/s, respectively.

There are differences in the values of the curves of identical features: tension at higher strain rate causes higher stress values at the same strain level. Despite the two orders of magnitude change in the strain rate, the stress difference at $\varepsilon = 100$ % strain is approximately 9%.

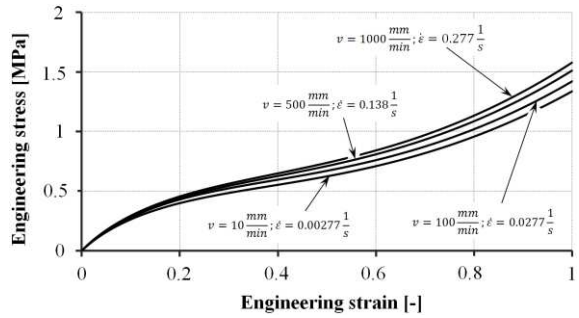
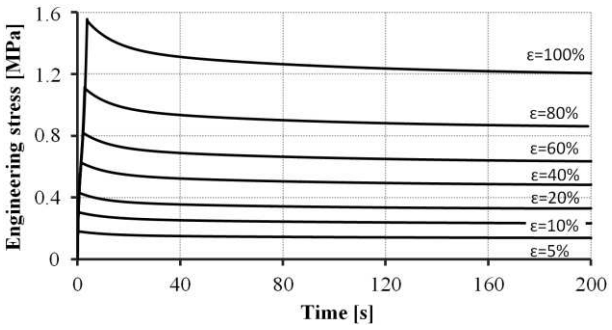
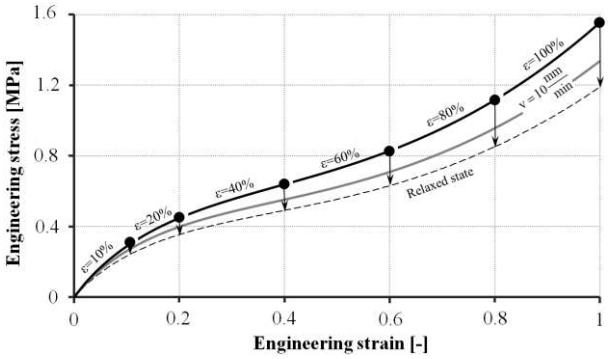


Figure 2

Engineering stress-strain curves of tensile tests at different strain rates



(a)



(b)

Figure 3

(a) Engineering stress-time and (b) stress-strain curves of relaxation measurements at different strain levels up to t = 200 s

In order to study the time-dependent behaviour of isoprene rubber, stress relaxation tests were performed on specimens, similar to the ones applied for tensile tests. During the tests, after setting the 60 mm fixing length, the specimens were loaded to 5, 10, 20, 40, 60, 80 and 100% strain levels at a speed of v = 1000 mm/min (0.27 1/s strain rate), and stress relaxation was measured for t = 200 s. Figure 3a shows the measured relaxation curves.

As can be seen, relaxation slowed down by t = 100 s at all strain levels. At t = 200 s, the differences between the maximum and relaxed values of the curves specified at each strain level are 28.68%, 26.39%, 24.61%, 23.46%, 22.99%, 22.77% and 22.64%, respectively.

Figure 3b shows the engineering stress-strain curves corresponding to the relaxation tests. The upload phases of relaxation tests can be considered as tensile tests of v = 1000 mm/min (similar to Figure 2). Furthermore, the figure specifies the relaxed stress values at each strain level after t = 200 s (see the broken line).

This broken curve can be considered as the relaxed tensile characteristic of the material.

As can be seen, the stress-strain curve of the 10 mm/min tensile test is very far from the relaxed state.

2 Analytical and Numerical Implementation of Finite Viscoelasticity

In engineering calculations, the behaviour of rubber is often considered to be independent of time, since calculations can be highly simplified this way. The theory of linear viscoelasticity can be applied if the material has considerable hysteresis at small strains. The theory of linear viscoelasticity is not appropriate for taking hyperelastic behaviour into consideration because, in this case, the stress-strain curve is not linear any longer. The theory of linear viscoelasticity was generalized by Simo in order to describe the mechanical behaviour of finite viscoelastic materials.

The II. Piola-Kirchoff stress (in the total Lagrange approach) by taking both strain and time dependence into account, is defined according to Eq. (3) [2]

$$S(\varepsilon^{GL},t) = S^{\infty}(\varepsilon^{GL}) + \sum_{i=1}^{n} T_i(t) \tag{3}$$

where $S(\varepsilon^{GL},t)$ is the II. Piola-Kirchoff stress depends on time and Green-Lagrange strain; $S^{\infty}(\varepsilon^{GL})$ is the II. Piola-Kirchoff stress in the relaxed state; while $T_i(t)$ is an external variable specifying the time-dependence of the material with reference to term i of an n-term viscoelastic spring-dashpot model (see below). As can be observed, the first part of Eq. (3) describes the strain while the second part describes the time dependence. Dependence of the material model on strain will be taken into consideration in later chapters by the so-called Signiorini hyperelastic material model [1, 2].

$$W(\varepsilon) = c_{10}\cdot(I_1(\varepsilon)-3) + c_{01}\cdot(I_2(\varepsilon)-3) + c_{20}\cdot(I_1(\varepsilon)-3)^2 \tag{4}$$

where $W(\varepsilon)$ is the specific strain energy density; c_{10}, c_{01}, and c_{20} are material constants; I_1 and I_2 are the first and second invariants of the Cauchy-Green strain tensor.

One of the most frequently applied spring-dashpot models demonstrating viscoelastic behaviour is the so-called Standard-Solid model, consisting of a linear spring parallel to the Maxwell element. The latter consists of a linear spring and a viscous element connected in series. A generalized Maxwell-model can be created by several Maxwell elements connected in parallel (see Figure 4), which -

similarly to the Standard-Solid model – can be used for modeling elastic and delayed elastic deformation components of rubbers. In applications where not only a qualitative but also a quantitative analysis is requested, a large number of Maxwell terms must be used (in many cases more than 20, see [5]).

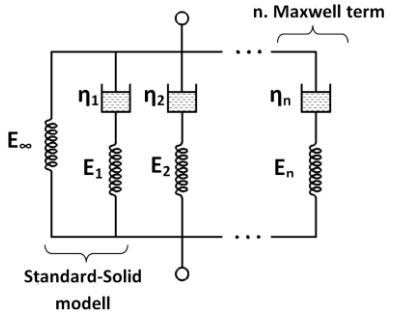


Figure 4
n-term generalized Maxwell-model

The relaxation modulus of the generalized Maxwell-model can be specified according to Eq. (5)

$$E_r(t) = E_0 - \sum_{i=0}^{n} E_i \cdot \left(1 - e^{-\frac{t}{\tau_i}}\right) \tag{5}$$

where $E_r(t)$ is the elastic modulus of the material at a given moment of relaxation; E_0 is the glassy modulus of the material; E_i and τ_i are the i-th modulus and relaxation time of the n-term generalized Maxwell-model. In practice, the i-th modulus of the generalized Maxwell-model is specified, instead of the E_i value, by an e_i dimensionless energy parameter.

$$e_i = \frac{E_i}{E_0} \qquad \text{and} \qquad \sum_{i=1}^{n} e_i = 1 - \frac{E_\infty}{E_0}. \tag{6}$$

Similarly to the theory of linear viscoelasticity, the external variable $T_i(t)$ in Eq. (3) can be expressed in the form of a convolution integral as specified in Eq. (7).

$$T_i(t) = \int_0^t e_i \cdot \dot{S}^0(t) \cdot e^{\frac{-(t-T)}{\tau_i}} d\tau \quad , \tag{7}$$

where $\dot{S}^0(t)$ is the time derivative of II. Piola-Kirchoff stress corresponding to the glassy state (see later).

Hereafter, the forms of Eq. (3) and (7) suitable for engineering calculations are specified with reference to a constant strain rate uniaxial tensile test. As a consequence of the convolution integral, calculations are performed incrementally

at Δt time intervals. The II. Piola-Kirchoff stress corresponding to the relaxed state is defined according to Eq. (8).

$$S^{\infty}(\varepsilon^{GL}) = \frac{\partial W^{0}(\varepsilon^{GL})}{\partial \varepsilon^{GL}}\left(1 - \sum_{i=1}^{n} e_i\right), \tag{8}$$

which, being expanded by the Signiorini material law can be seen in Eq. (9) and (10) for the relaxed and glassy states.

$$S^{\infty}(\varepsilon^{GL}) = \left[(c_{10} + c_{20}) \cdot (I_1(\varepsilon^{GL}) + c_{01} \cdot (I_2(\varepsilon^{GL})\right](1 - \sum_{i=1}^{n} e_i) \tag{9}$$

$$S^{0}(\varepsilon^{GL}) = \left[(c_{10} + c_{20}) \cdot (I_1(\varepsilon^{GL}) + c_{01} \cdot (I_2(\varepsilon^{GL})\right] \tag{10}$$

By substituting the values of ε^{GL} in Eq. (9) and (10) by Eq. (11), the equations can be made dependent on t (v denotes the speed of tension).

$$\varepsilon^{GL} = \frac{1}{2}\left[\left(\varepsilon^{m}\right)^2 - 1\right] \qquad \text{where} \qquad \varepsilon^{m} = \frac{\Delta l}{l_0} = \frac{v \cdot t}{l_0} \tag{11}$$

The t dependent expression $S^0(t)$ can be used for specifying the external variable $T_i(t)$ in the form of Eq. (12).

$$T_i(t) = \beta_i \cdot e_i\left(S^0(t) - S^0(t - \Delta t)\right) - \alpha_i \cdot T_i(t - \Delta t), \tag{12}$$

where

$$\alpha_i = 1 - e^{\frac{-\Delta t}{\tau_i}}, \tag{13}$$

$$\beta_i = \alpha_i \cdot \frac{\tau_i}{\Delta t}. \tag{14}$$

The output parameters of the calculation are the Green-Lagrange strain and II. Piola-Kirchoff stress pairs. For the sake of comparability with the measurements, the stress and strain values were converted into engineering values by Eq. (15) and (16).

$$\varepsilon^{m} = \sqrt{2 \cdot \varepsilon^{GL} + 1} - 1 \tag{15}$$

$$\sigma^{m} = \sigma^{PK} \cdot \left(\varepsilon^{m} + 1\right) \tag{16}$$

The calculation scheme can predict the mechanical behaviour of a rubber-like material by using any type of hyperelastic material law, if the Cauchy-Green strain tensor associated with the dominant type of loading (uniaxial tension, biaxial tension, simple shear and planar shear) is known and Eq. (4) can be expressed by its invariants. As seen, the above calculation schema works with the instantaneous values. Naturally a calculation scheme to be based on relaxation values can also be formulated [4, 7]. The resulted characteristics and values will be the same but the forms of equations will differ.

In the case of complex geometry or stress state, for example the finite element method (FEM) can be used to predict the material behaviour. [1, 2, 5]. In the MSC. Marc commercial FE software, the input parameters of a visco-hyperelastic analysis are constant material parameters defining the strain energy density corresponding to the glassy state (c_{ij}), as well as dimensionless energy parameters (e_i) and relaxation times (τ_i) [2]. In order to take into consideration the incompressible nature of elastomers, special elements with Hermann formula can be applied.

3 Parameter Identification Based on Stress Relaxation Test

It is time-consuming and expensive to measure the time dependent behaviour of viscoelastic materials; therefore they are primarily used if the target is to describe the complex mechanical behaviour of the material in a broad frequency and temperature range, for which dynamic mechanical thermal analyzer (DMTA) measurements are widely applied. By shifting the isotherms measured by DMTA based on the time-temperature superposition, large generalized Maxwell-models (number of terms can reach 40) can be produced to cover frequency ranges which exceed even 20 orders of magnitude [6].

In the majority of problems occurring in engineering practice, viscoelastic models of a small number of terms can be used to describe time and frequency dependent behaviour with appropriate accuracy. These models represent the dynamic behaviour of the material in only a small frequency range; in the literature, it is recommended that the parameters be determined primarily by stress relaxation tests [2, 10].

In the event of stress relaxation, the rubber undergoes a completely elastic deformation as a consequence of a theoretically abrupt excitation of expansion. Then the strain is kept constant and the rubber becomes delayed elastic with the stress decreasing from the initial maximum value, thus undergoing stress relaxation. In real tests, abrupt excitation of expansion is not possible: the loading phase is realized with a finite speed, so the relaxation partly takes place before the strain becomes constant. As a result, the maximum stress will not be identical with the maximum stress of the material with no relaxation in the loading phase.

The majority of FE softwares (Msc. Marc, Abaqus, Ansys) have built-in algorithms to fit the parameters of a characteristically 10-term generalized Maxwell-model to the relaxation test data. The curve fitting algorithm of Msc. Marc performs this fitting to a shear modulus vs. time curve derived from the measurement. In this case, Eq. (5) contains the shear modulus of the material instead of its tensile modulus. In order to determine the shear modulus, the force-time curve yielded by the measurement must be converted into an engineering

stress-time curve by using Eq. (2) (see Figure 3a). The momentary or relaxation modulus of the material (E_r) can be calculated by dividing the measured engineering stress values by the strain ε_0 applied in the relaxation measurements. The shear modulus can be calculated on the basis of the relaxation modulus curve by

$$G = \frac{E}{2 \cdot (1+\nu)} \approx \frac{E}{3} \tag{17}$$

where ν is the Poisson ratio of the material (in the case of incompressibility ν=0.5). In the course of fitting, the value of the glassy (or instantaneous) shear modulus G_0 is also produced. Obviously, this is not identical with the real glassy modulus of the material because the loading phase was realized with a finite strain rate in the stress relaxation measurement. The traditional approach presented so far is only suitable for producing the parameters of a generalized Maxwell-model corresponding to small strain viscoelasticity, due to the fact that the dependence of G_0 on strain is not taken into account. In order to introduce it, [2] proposes to substitute the value of E_0 by a two parameter Mooney-Rivlin hyperelastic material law. The parameters can be estimated by using Eq. (18) and (19).

$$E_0 = 6 \cdot (c_{10} + c_{01}) \tag{18}$$

$$\frac{c_{01}}{c_{10}} = \frac{1}{4} \tag{19}$$

In the manner described, the parameters of viscoelastic model were produced on the basis of stress relaxation measured at strain level of 5, 60 and 100% (see Figure 3a). The parameters are shown in Table 2.

Table 2
Parameters specified on the basis of stress relaxation

	Strain level [%]		
	5	60	100
e_1 [-]	0.0625	0.122	0.1176
e_2 [-]	0.1289	0.0755	0.0870
e_3 [-]	0.1076	0.0425	0.0309
τ_1 [s]	0.1124	10.007	10.3299
τ_2 [s]	11.0958	78.1938	83.7698
τ_3 [s]	99.6630	123.54	137.777
E_0 [MPa]	3.8804	1.36624	1.5461

Using these parameters, the FE method was applied for calculating the stress-strain and stress-time curves at a speed of 1000 mm/min. The material constants of the two parameter Mooney-Rivlin material law applied in the calculation were computed from the value of E_0 specified in Table 2, using Eqs. (18) and (19). The FE model used is shown in Figure 5.

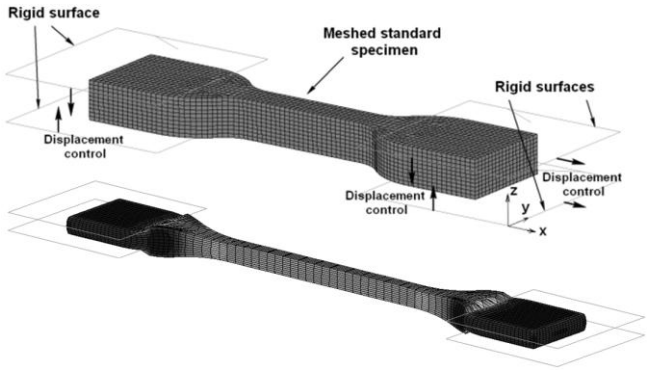
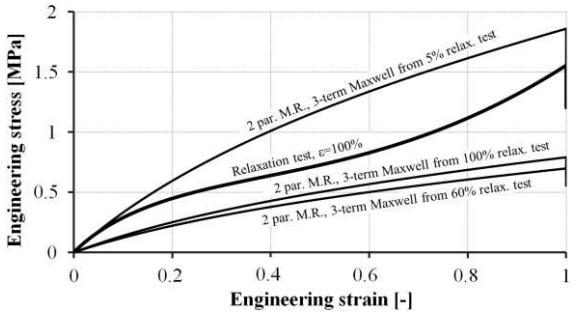
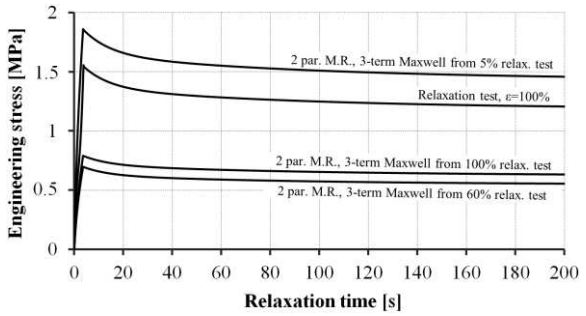


Figure 5
FE model and deformed shape of a standard specimen at 60 % strain

The model consists of 10400 linear hexahedron elements. The coefficient of friction between the rigid and meshed parts was $\mu = 2$ in order to avoid slippage. The rigid surfaces shown in Figure 5 approach each other according to the arrows indicated during the first 20 s of the calculation, in a way that the initial thickness ($b_0 = 10$ mm) of the model is reduced to 6 mm. The next 300 s is a static phase of relaxation, followed by the motion of rigid surface in direction x, according to Figure 5. The speed of the motion was constant up to a prescribed strain value. The stress relaxation occurs by keeping the rigid surfaces in a fixed position. Similarly to the measurements, force and elongation values were collected from the calculation and converted into stress-strain and stress-time curves. Figures 6a and 6b show the results calculated for the phases of loading and relaxation, respectively. The calculations in Figure 6 are based on the viscoelastic parameters given in Table 2 and the Mooney-Rivlin parameters (c_{01}, c_{10}) computed from the glassy modulus (E_o) by Eqs. 18-19.



(a)



(b)

Figure 6

Measured and calculated (a) stress-strain and (b) stress-time curves of the stress relaxation measurement

In order to quantify the differences between the curves, a so-called standard error is applied. In the case of an n number of x and y sampling values, the error can be calculated as

$$\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}(x_i-y_i)^2}\,. \tag{20}$$

The behaviour measured is overestimated by the material law derived from stress relaxation at a strain of 5% – the standard error being 0.294 MPa – while it is significantly underestimated by those derived from relaxation at strain of 60% and 100 % with a standard error of 0.637 MPa and 0.560 MPa, respectively. One of the reasons for this is that at $\varepsilon = 5\%$, the material had much less time to relax than at $\varepsilon = 60$ or 100%, so the E_0 glassy modulus value determined here approximates the real value better. This difference is also affected by the ratio specified in Eq. (19), which is a constant value independent of the material composition and test conditions. The characteristics of the curves calculated also considerably differ from the characteristics measured since the two parameter Mooney-Rivlin material law cannot provide a stress-strain curve having an inflexion point, which is typical with rubbers over a certain strain level. As indicated by the standard errors between the curves defined, the method proposed by [2] can be used for modeling the behaviour of rubbers primarily in the range of small strains, since in this case the stress relaxation occurring in the course of loading causes a smaller problem. Similarly, the difference between the behavior of the two-parameter Mooney-Rivlin material law and the real rubber is smaller at small strains than at large ones.

In order to partially solve the problems of the material laws derived from the relaxation test, the authors propose to apply a multi-parameter – e.g. the Signiorini hyperelastic – material model to be determined from the stress-strain curves of tensile tests. According to this, the free parameters of the hyperelastic model were

determined from tensile tests conducted at different speeds (see Figure 2) by using the curve fitting algorithm of MSC. Marc. Table 3 shows the fitted parameters and their ratios.

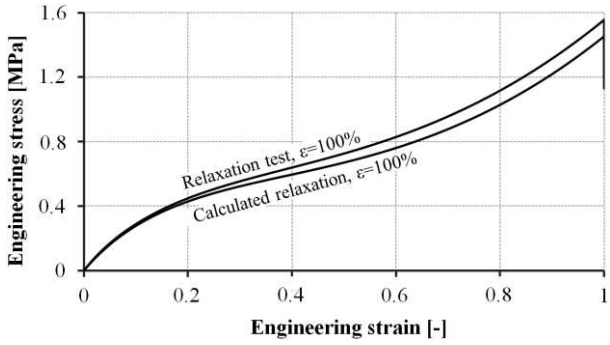
Table 3
Model parameters obtained from curve fitting

	$v = 10 \frac{mm}{\min}$	$v = 100 \frac{mm}{\min}$	$v = 500 \frac{mm}{\min}$	$v = 1000 \frac{mm}{\min}$
c_{01}[MPa]	1.2665	1.289	1.2835	1.3317
c_{10}[MPa]	-0.6382	-0.6697	-0.6905	-0.6774
c_{20}[MPa]	0.1104	0.109	0.1099	0.1172
c_{01}/ c_{10} [-]	-1.9845	-1.9247	-1.8588	-1.9659
c_{10}/ c_{20} [-]	-5.7808	-6.1440	-6.2830	-5.7799

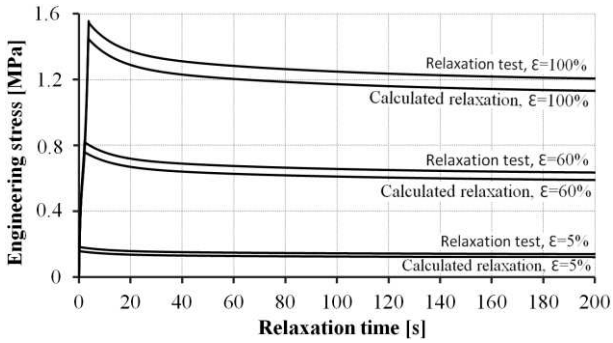
The ratios of parameters derived from separate tensile tests indicate small standard deviation; therefore, as a good approximation, they can be considered as identical regardless of the strain rate. Hereafter, the ratios of the 1000 mm/min tensile test will be used in the calculations.

As a first step, the parameters of the hyperelastic material model were recalculated by using the parameter ratios (see last column in Table 3) and the glassy modulus (E_0 = 3.88 MPa from Table 2.) determined. To do this Eq. (4) was differentiated twice with respect to ε, yielding the E(ε) function. Substituting the value ε = 0 will produce the expression to describe the connection of E_0 and the constant material parameters as shown in Eq. (21).

$$E_0 = 6 \cdot (c_{10} + c_{01}) \tag{21}$$



(a)



(b)

Figure 7

Comparison of measured and calculated (a) stress-strain and (b) stress-time curves

As can be seen, Eq. (21) corresponds to Eq. (18) proposed by [2] for the two-parameter Mooney-Rivlin material law. Based on the parameter ratios and Eq. (21), the recalculated material parameter values are c_{01} = 1.3163 MPa, c_{10} = 0.6696 MPa, and c_{20} = 0.1158 MPa, respectively. Figure 7a shows the measured and calculated (by using the recalculated parameters) loading phases of relaxation tests at $\varepsilon = 100\%$.

As can be observed, the material law produced is capable of approximating the values measured much better than the calculation method proposed by [2]. In this case, the standard error of the loading phase is 0.0629 MPa, which is on an order of magnitude smaller than the former value. Figure 7b shows the measured and calculated relaxation phases of the relaxation test at 5%, 60% and 100% strain.

In all the cases, the calculations underestimate the measurements, which is a consequence of the lower glassy modulus (E_0) value resulting from the relaxation test. The glassy modulus coming from stress relaxation measurement is smaller to the real value due to the stress relaxation during the loading phase. In the case of relaxation, the standard error between the calculation and the measurement is 0.01945 MPa, 0.0466 MPa, and 0.07519 MPa, respectively.

4 Parameter Identification from Simple Tensile Tests

The previous chapter showed the possibility of producing the parameters of a material law representing real mechanical behaviour through a stress relaxation test of small strain performed at the highest strain rate possible. However, the parameters can be obtained without a relaxation test, simply from two tensile tests of different speeds [11]. An advantage of this method is that the required material parameters, which are able to describe the mechanical behavior of the material in

a limited frequency and time range important in practice, can be produced with a minimum amount of tests.

The method is based on the recognition that the tensile tests with different strain rates result in different stress values at the same level of strain due to stress relaxation (Figure 2). From these differences the parameters of the spring-dashpot model (e.g. generalized Maxwell-model) can be identified. Figure 8 shows the block diagram of the method.

As seen, we need to calculate the first partial derivatives of the stress-strain curves of tensile tests measured at two different strain rates. This yields the elastic modulus-strain curves ($E_I(\varepsilon)$ and $E_{II}(\varepsilon)$). Then the ratio of $E_I(\varepsilon)$ and $E_{II}(\varepsilon)$ values is calculated at different strains ($E_m(\varepsilon)$). As a next step, the expression derived from Eq. (5) for the generalized Maxwell-model ($E_m^{fitted}(\varepsilon)$) is fitted to the $E_m(\varepsilon)$ values obtained by substituting the time parameter t with an expression including the length of the specimen, the tension speed and the strain (similarly to Eq. (11)). The fitting itself can be performed with the method of least squares for models with a smaller number of terms or by genetic algorithm in the case of a higher number of terms. It is also possible to apply one of the increasingly-used optimization methods, e.g. the differential evolution (DE) algorithm detailed in [12].

The parameters of a 3-term generalized Maxwell-model were determined by the built in genetic algorithm of Matlab [13], using the 1000 mm/min and 10 mm/min measurement results of isoprene rubber. Table 4 shows the identified parameters.

Table 4
Identified parameters

	e_i [-]	τ_i [s]
term 1	0.0756	0.101
term 2	0.0615	8.120
term 3	0.2039	91.891

Based on the analysis of the fitted parameters, it can be stated that the relaxation times correspond, with good approximation, to the relaxation times specified on the basis of the stress relaxation test at $\varepsilon = 5\%$, but the sum of dimensionless energy parameters is $\Sigma e_i = 0.299$ according to the relaxation measurement, while $\Sigma e_i = 0.341$ on the basis of tensile tests.

If the viscoelastic parameters are known, then the glassy modulus can be determined from the equations presented in Figure 8. Contrary to the linear viscoelastic materials, where the glassy modulus has no strain dependency in the case of large strain viscoelasticity, the glassy modulus depends on the strain. Figure 9 shows the glassy modulus determined from the 1000 mm/min uniaxial tensile test in function of strain.

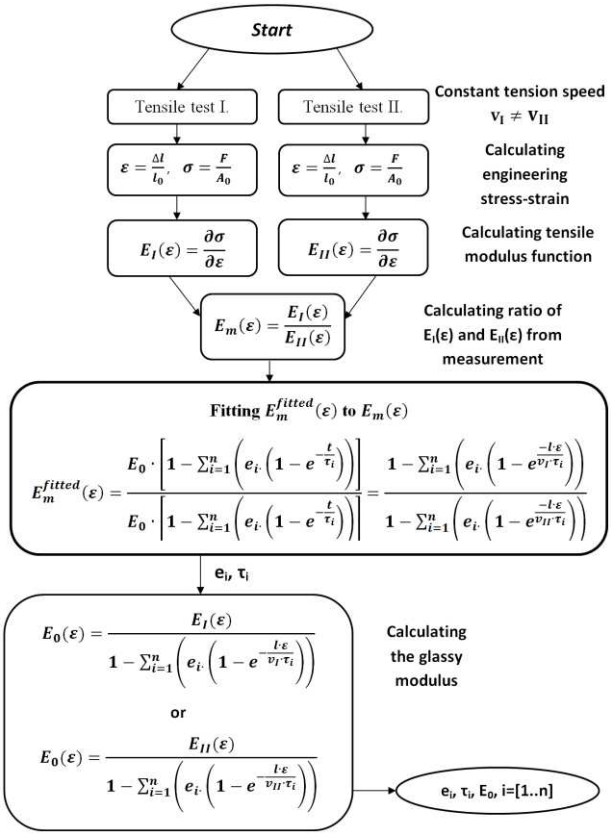


Figure 8
Block diagram of the tensile test based parameter identification method

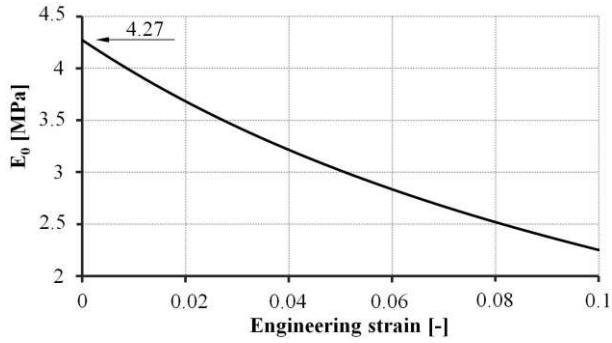


Figure 9
Glassy modulus identified by curve fitting in function of strain

The glassy modulus curve depicted is not linear and is not defined at $\varepsilon = 0$. Its value for the smallest ε is 4.27 MPa, which can be considered as the E_0 glassy modulus of the material. The identified glassy modulus exceeds the 3.88 MPa value of the glassy modulus determined from the stress relaxation test at $\varepsilon = 5\%$ strain. The glassy modulus (E_0) and the parameter ratios in Table 3 can be used to determine the parameters of the Signiorini material law (c_{01} = 1.43798 MPa, c_{10} = -0.73146 MPa, and c_{20} = 0.12655 MPa).
Figure 10 shows the measured and calculated characteristics of the relaxation tests measured at 5%, 60% and 100% strain, using the hyperelastic and viscoelastic parameters identified.

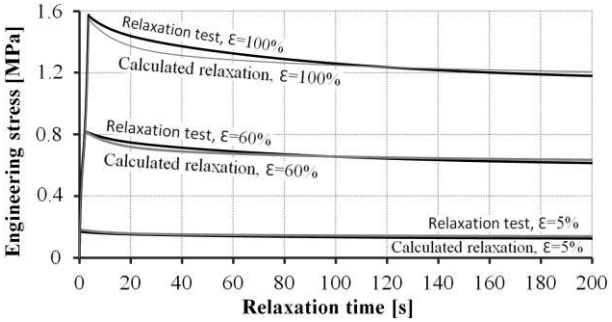
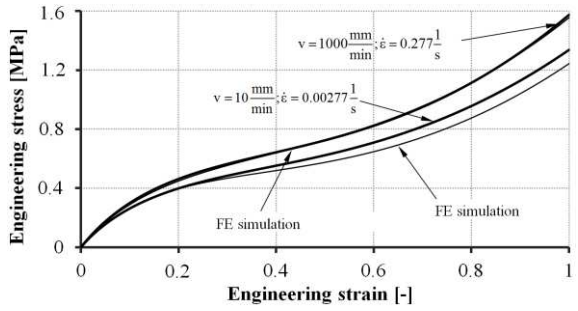


Figure 10
Comparison of simulation and measurement

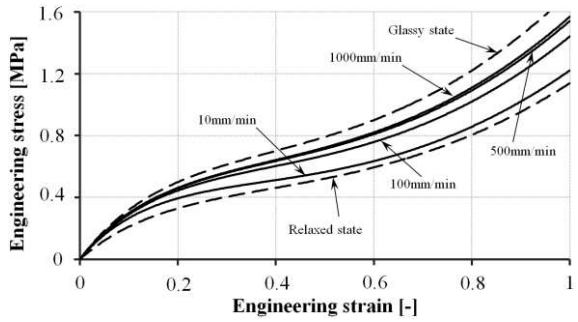
As can be seen, the simulation differs slightly from measurement. After the nearly identical stress maximum, the calculated relaxation curve does not proceed parallel with the measured one, but intersects it at t = 120 s. The relative error between the measurement and the calculation is 0.01001 MPa, 0.0164 MPa and 0.03655 MPa, respectively.

Figure 11a shows the measured and calculated tensile tests at 1000 mm/min and 10 mm/min tensile speed. At 10 mm/min the agreement is less good but the accuracy is still acceptable. The standard error of the simulation at higher speed is 0.008442 MPa, and that of the simulation at lower speed is 0.05626 MPa compared to the measurements.

The engineering stress-strain curves of the tensile tests were determined by analytical calculations as well, as shown in Figure 11b. The figure also shows the states corresponding to the glassy and relaxed state. The relaxed state shown in Figure 11b is lower than the one identified by measurement (Figure 3b). This is partly due to the fact that stress relaxation tests lasted for 200 s, which does not ensure that the final relaxed state is identified.



(a)

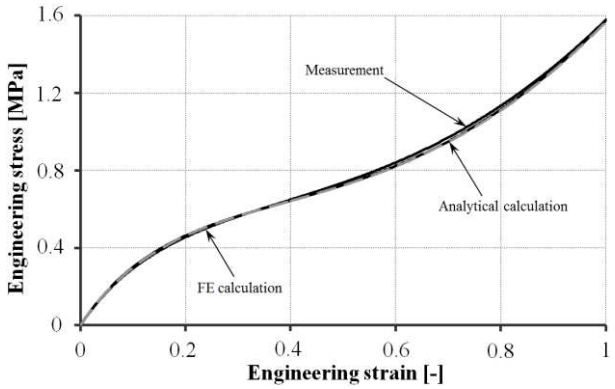


(b)

Figure 11

(a) Calculated tensile tests of various speeds; (b) comparison of the engineering stress-strain curves of tensile tests with the calculated characteristics

Figure 12a shows the stress-strain curve of the measurement at 1000 mm/min, and Figure 12b shows that of the measurement at 10 mm/min, together with the results of the FE calculation using the material law set up on the basis of tensile tests and those of analytical calculations.



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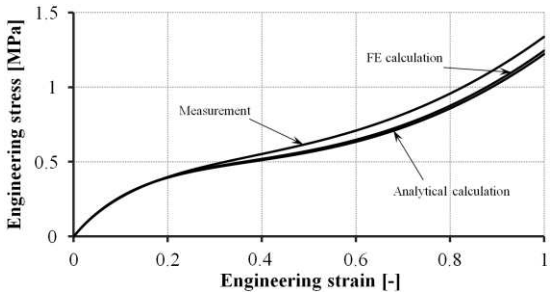

(b)

Figure 12
Engineering stress-strain curves of the measurements, FE and analytical calculations at (a) 1000 mm/min and (b) 10 mm/min

As can be observed, the calculations at the higher speed approximate the results measured perfectly; the standard error of the FE calculation is 0.008442 MPa, while the error of the analytical calculation is 0.008398 MPa. As compared to the 10 mm/min measurement, the error of the FE calculation is 0.05626 MPa, while the error of the analytic calculation is 0.0672 MPa. The slight difference between the analytical and the FE calculations presumably follows from the discretization applied in the numerical adaptation of the equations presented in Chapter 2.

Conclusions

In the present paper, a new parameter identification method has been presented. The proposed method enables the parameters of large strain generalized Maxwell-model to be determined on the basis of constant strain rate tensile tests. The application of the method has been presented for a specimen made of isoprene rubber. It has been proved that the method is able to identify large strain viscoelastic parameters of Maxwell-model with reasonable accuracy. In the event that one has only a standard tensile tester for material characterization, the proposed method is especially useful.

It will be shown in another paper that the proposed method can be used not only in the case of uniaxial tension, but also in the case of biaxial tension, simple shear, and planar shear.

Acknowledgements

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Evaluation Criteria for Object-oriented Metrics

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Abstract: In this paper an evaluation model for object-oriented (OO) metrics is proposed. We have evaluated the existing evaluation criteria for OO metrics, and based on the observations, a model is proposed which tries to cover most of the features for the evaluation of OO metrics. The model is validated by applying it to existing OO metrics. In contrast to the other existing criteria, the proposed model is simple in implementation and includes the practical and important aspects of evaluation; hence it suitable to evaluate and validate any OO complexity metric.

Keywords: Evaluation Criteria; Measurement; Verification; OO Metrics; Weyuker's Property; language independency; additive nature of metrics

1 Introduction

Several researchers have proposed a variety of criteria [1-11] for evaluation and validation to which a proposed software metric should adhere. Amongst them, we can mention validation through measurement theory [2, 4, 6], IEEE standards [5] Kaner's framework [3], and Weyuker's properties [11]. However, most of the existing evaluation and validation criteria were proposed when procedural languages were dominant. After the adaptation of OO languages by the software industry, not too much effort has been made to develop a model/ framework for evaluating software complexity measures in the OO domain. There are some proposals for OO languages [12-15]; however, most of them cover only specific features of evaluation. For example, Zuse's properties [15] for OO metrics are mathematical in nature and based on principles of measurement theory. The lack of proper guidelines for evaluation and validation of OO metrics motivate us to develop a new evaluation criterion which includes all the features required for evaluation of the OO metrics. For achieving this goal, first we have analyzed the available validation and evaluation criteria, extracted their important features, suggested additions/modifications (if required), then presented them in a formal way. The validity of the proposed model is evaluated by applying eleven different well-known OO metrics. These metrics are described in the next section.

OO metrics are measurement tools to achieve quality in software process and product. However, in general, software measurement has not yet achieved the needed degree of maturity [9] and it needs standardization [16]. Existing proposals, such as Weyuker's properties [11] and the application of measurement theory in software engineering [2, 4, 6, 17, 18], are a topic of discussion [19-23]. We have also worked in the related area of software measurement and presented several papers. We have presented a paper on the usefulness of Weyuker's properties for procedural languages [24]. In another work, we have analysed how Weyuker's properties are used by the developers of three OO metrics [25]. We have previously performed experimentations to analyse the current situation of standard measurement activities in small and medium software companies [26]. We have also performed a study on the situation of the empirical validation of software complexity measures in practice, and we accordingly proposed a model [27]. The applicability of measurement theory on software complexity measures is also investigated in one of our previous works [22]. In the present paper we analyse the present practices used for evaluation and validation of OO metrics, and we accordingly present a model for evaluating OO metrics. We also propose a framework for evaluating software complexity measures but, the present paper is specifically for OO metrics, since OO languages do not share the same features with procedural languages.

Research Problem and Methodology

The literature survey shows that there exist lapses in the measurement process in software engineering. Following this, several researchers have tried to propose a variety of criteria [1-15, 28-30] for different types of measurements in software engineering. OO programming, which is a relatively new programming paradigm in comparison to procedural languages, has received a lot of acceptance from the industry. Several researchers have also proposed software metrics to evaluate its complexity. However, a lack of standard guidelines makes it difficult to propose useful metrics based on a strong theoretical scientific foundation.

We are motivated to present this paper by the following research questions:

Do the exiting criteria for the evaluation of OO metrics evaluate most of the features required for an OO metric (1)?

Should all the features suggested for metrics also be applicable to OO metrics? (2)

To answer these questions, we keep the agenda of the present work as follows;

1 To evaluate the existing criteria which are used for evaluating OO metrics.

2 To extract the important features from the existing criteria for evaluating OO metrics (several well-known metrics are applied on these criteria to extract the features which are useful for OO metrics).

3 To propose a model (based on the evaluation of the existing criteria) which is based on sound scientific principles and which is also easy to adopt by the community.

4 To validate the model by examining it against several well-known and newly proposed metrics.

The initial version of the present work was presented in ICCSA 2009 [31]. In this paper [31], we evaluated each of Weyuker's properties for OO metrics based on experimentation. In addition, we have evaluated all the considered OO metrics against language independency and additive property. In the present work, we have extended our previous work. We are evaluating the applicability of measurement theory on OO metrics. Based on the evaluation of measurement theory, scale measurement, language independency and Weyuker's properties, we propose a model for the evaluation of OO metrics. This model for the evaluation of the OO metrics includes all the required features which are essential for the evaluation and validation of OO metrics.

The remainder of this paper is organized as follows: The evaluation of the applicability of Weyuker's properties and the principals of measurement theory to OO metrics is given in Section 2. A brief analysis of existing important validation criteria is also given in the same section. The proposed model is given in Section 3. The observations are summarised in Section 4. Lastly, the conclusions drawn from the work are summarised.

2 An Analysis of Existing Validation Criteria

Several authors [12-15, 32] have attempted to provide the features of OO metrics and systems. This section provides a brief discussion of some of the important existing evaluation and validation criteria for OO metrics. The rest of the validation criteria are either related to them or specially confined to a single attribute of a software measure. For example, in [14] the authors have emphasized that object-oriented metrics should be evaluated through some quality attributes and have left out other issues (for example practical usefulness) which are also important for the complete validation process.

Weyuker's [11] properties are well-established evaluation criteria for software complexity measures. A good complexity measure should satisfy Weyuker's properties. Although she proposed the properties at the time when procedural languages were dominant, even at present these properties are also valuable to evaluate OO metrics. A significant number of researchers [33-37] have evaluated OO metrics by the complexity properties proposed by Weyuker [11]. For example, Chidamber and Kemerer [33] have applied them for the theoretical evaluation of their OO metrics and, due to the high popularity and acceptance of Chidamber et

al.'s metrics, these properties are assumed to be accepted as an evaluation criterion for OO metrics [25]. Consequently, several researchers have used these properties for the evaluation of their object-oriented metrics. Other examples that follow Chidamber et al.'s criteria for theoretical evaluation include a complexity metric based on the different constituents of the components, such as inheritance of classes, methods and attributes proposed by Sharma Kumar & Grover [36], and two OO software design metrics for exception-handling proposed by Aggarwal, Singh, Kaur & Melhotra [35], who have also used Weyuker's properties for theoretical evaluation. We have observed that, in their evaluation, Weyuker's properties have been misunderstood [25].

Measurement theory provides strong rules for the evaluation of software complexity measures. Evaluation through measurement theory proves the scientific basis of the proposed measure. It also proves that the proposed measure actually measures what it is supposed to measure. However, there is a problem in the applicability of measurement theory to software engineering. It is not easy to find a single method that can be accepted by all the software community. Then the question arises: which one is the valid measurement? Some authors put emphasis on representation condition [4], while others emphasized extensive structure [17]. In the next section we also evaluate the applicability of the principals of measurement theory to OO metrics.

Zuse [15] proposed properties of OO software measure based on measurement theory. The validation criteria for complexity measure related to measurement theory states that a valid measure should assume an extensive structure. Zuse himself proved that software measures for OO languages mostly do not assume an extensive structure. Zuse has also given more properties for this purpose, but most of them are not in common use. One of the reasons for the minimal success of these properties is due to fact that these properties are not easy to understand. We will discuss these properties in more detail in Section 2.2.

Linda [14] identified that efficiency, complexity; understandability, reusability, testability and maintainability are five attributes for measuring software quality. An OO metric should measure one or more of these attributes and must evaluate the object-oriented concepts, classes, methods, cohesion, inheritance, polymorphism, number of messages, and coupling. His proposal is concise and useful. We consider Linda's suggestion in our model.

Radu [13] has proposed a new mechanism named detection strategy for increasing the relevance and usability of metrics in OO design by providing a higher-level means for interpreting measurement results. He suggested that four criteria are useful for good design: low coupling, high cohesion, manageable complexity, and proper data abstraction. Radu's proposal is related to the features of OO software development.

We have considered eleven OO complexity metrics. We have applied all these metrics to existing evaluation and validation criteria. We have also applied these

metrics to validate our proposed model. We have considered the weighted methods per class (WMC), depth of inheritance tree (DIT), number of children (NOC), coupling between objects (CBO), response for a class (RFC), lack of cohesion in method (LCOM), [33] weighted class complexity (WCC) [37], complexity measures for object-oriented program based on entropy (CMBOE) [34], component complexity (CC) [36], number of catch blocks per Class (NCBC) and exception handling factor (EMF) [35]. The first seven metrics are taken from Chidamber' and Kemerer's paper [33]. These metrics were proposed in 1994 and presently they are the most accepted metrics for the evaluation of OO code. CC was proposed by Sharma, Kumar & Grover [36] in 2007. WCC was proposed by Misra and Akman [37] in 2008. NCBC and EMF were proposed by Aggarwal, Singh, Kaur and Melhotra [35] in 2006. CMBOE [34] is based on the concept of entropy and was proposed in 1995. One common thing amongst all these metrics is that all of them use Weyuker's properties. This is advantageous for us because we are also evaluating the relevance of Weyuker's properties. Further, all the complexity measures/metrics under consideration are available online; we do not describe the metrics further but instead we recommend our readers to follow [33-37], for the details of these metrics.

2.1 Weyuker's Properties and OO Metrics

We have evaluated all the above complexity measures against each of Weyuker's properties. Table 1 has been constructed based on the applicability of Weyuker's properties to different complexity measures. The data for this table is collected from the original papers, where they used Weyuker's properties for the theoretical evaluation of their metrics.

Table 1
Different OO measures and Weyuker's properties

P. N	WMC	DIT	NOC	CBO	RFC	LCOM	WCC	CMBOE	CC	NCBC	EMF
1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Y	Y/Y/N	Y	Y	Y	N	Y	N	Y	N	N
6	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
7	Y	Y	Y	Y	Y	Y	N	N	Y	Not used	Not used
8	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
9	N	N	N	N	N	N	N	Y	Y	Not used	Not used

P. N: property number, Y: Yes (satisfied), N: No (not satisfied)

Misra and Akman [25] have evaluated the applicability of Weyuker's properties to component complexity (CC) [36], number of catch blocks per class (NCBC) and exception handling factor (EMF) [35], and they have demonstrated how these properties have been misunderstood when applying for their measures. In their work [25], the authors have applied Weyuker's properties to these metrics in a concise way. We extend their work and now evaluate the practical applicability of these properties with eleven OO metrics.

Based on the observations of Table 1, we have drawn the following conclusion for the applicability of each Weyuker property to evaluate any OO metric. Weyuker's properties were initially proposed for procedural languages. We present these properties for the OO domain by considering class [25] as a basic unit instead of program bodies.

Property 1: $(\exists P)\ (\exists Q)\ (|P| \neq |Q|)$. Where P and Q are the two different classes

This property states that a measure should not rank all classes as equally complex.

From Table 1, it is discovered that all complexity measures satisfy this property. Since not all classes can have the same value for a metric, all measures satisfy this property.

If any measure ranks all classes as equally complex, then it is not easy to say it is an effective measure. Most of the metrics satisfy this property.

The above discussion shows that this property is not very valuable for OO metrics.

Property 2: Let c be a non-negative number, then there are only a finite number of classes and programs of complexity c

This property states that there are only a finite number of classes of the same complexity.

Since the universe of discourse deals with a finite set of applications, each of which has a finite number of classes, this property will be satisfied by any complexity measure at the class level. Here, c is assumed to be the largest possible number, and should be represented as an upper-bound on the size of the program bodies.

As shown in Table 1, Weyuker's second property is satisfied by all complexity measures. Since this property is not capable of differentiating between complexity measures for OO languages, and since any sensible OO measure at class level should satisfy this property, it is also a property that is not useful for the evaluation of OO metrics.

Property 3: There are distinct classes P and Q such that $|P| = |Q|$

This property states that there are multiple classes of the same complexity.

In other words, this property states that even if there exist different classes, the complexity of these classes may be the same. All the complexity measures

mentioned satisfy this property as given in Table 1. This is due to the fact that in complexity measures, we can find several classes having the same metric value.

Property 2 and property 3 evaluate the same conclusion for any complexity measure. If there exist multiple classes of equal complexities, it also proves that the number of multiple classes is finite as is represented by property 2. For OO metrics, we can consider this property, since it also reflects property two.

Property 4: $(\exists P)\ (\exists Q)(P \equiv Q\ \&\ |\ P\ | \neq |\ Q\ |)$

This property states that implementation is important. If there exist classes P and Q such that they produce the same output for the same input. Even if the two classes have same functionality, they are different in the details of implementation. Or, if two programs consisting of many objects have the same functionality, they are different in the details of implementation. This property can be used for the purpose of evaluating OO metrics.

This property is also satisfied by complexity measures given in Table 1. This is due to the fact that even if two classes of design perform the same function, the details of the design matters in determining the metric for the class. The choice of the number of methods is a design decision and independent of the functionality of the class. In view of the discussion, this property is satisfied by all complexity measures.

Property 5: $(\forall P)\ (\forall Q)\ (|\ P|\ \leq |\ P; Q|\ \&\ |Q\ | \leq |\ P; Q\ |)$

This property states that, if the combined class is constructed by class P and class Q, the value of the class complexity for the combined class is larger than the value of the class complexity for class P or class Q.

If we evaluate the complexity measures given in Table 1 against this property, we find that this property is not satisfied by LCOM, DIT, CMBOE, NCBC, and EMF.

The failure of this property by LCOM is because the number of non-empty intersections will exceed the number of empty intersections [33]. DIT tree also does not satisfy this property for any special case, when for any two classes P and Q are combined, and when one is the child of the other [33]. CMBOE also does not satisfy this property [34]. For some cases of NCBC and EMF, they also do not satisfy this property. The method the developer of NCBC and EMF suggested, given that this property is not satisfied by any of the measures, was not appropriate [25]; it is possible that this property is not satisfied by these measures.

As a conclusion, this property is worth considering for the purpose of evaluating OO metrics.

Property 6a: $(\exists P)\ (\exists Q)(\exists R)(\ |P|=|\ Q\ |)\&\ |P;R\ | \neq |\ Q; R\ |)$

6b: $(\exists P)\ (\exists Q)\ (\exists R)\ (\ |\ P\ | = |\ Q\ |).\ \&\ |\ R; P\ | \neq |\ R; Q\ |)$

This property shows the non-equivalence of interaction. Also this is a contextual property; it states that, if a new class is appended to two classes which have

the same class complexity, the class complexities of the two newly combined classes are different, or the interaction between P and R can be different than the interaction between Q and R, resulting in different complexity values for P+ R and Q + R. This is also an important property, so we may use it as one of the evaluating criteria for OO complexity measures.

From Table 1, it is found that all complexity measure satisfy this property except WCC. All the measures satisfy this property because the interaction between the two classes, P and R, can be different from that between Q and R, resulting in different complexity values. For WCC, the cognitive weights of the methods and the number of attributes are fixed for any program. Joining programs *R* with *P* and *Q* adds the same amount of complexity; hence, property 6 is not satisfied by this measure.

Property 7: There are program bodies P and Q such that Q is formed by permuting the order of the statements of P, and ($|P| \neq |Q|$)

This property states that permutation is significant. It means that the permutation of the elements within the item being measured can change the metric values. The purpose is to ensure that the metric values change due to the permutation of classes. According to Chidamber and Kemerer [33], in the case of OO programming in any class or object, changing the order in which the methods or attributes are declared does not affect the order in which they are executed. Moreover, they argue that this property is meaningful in traditional programming languages but not for OO programming. In this respect, all Chidamber et al.'s metrics are satisfied by this property. For NCBC and EMF, the authors have also applied Chidamber et al.'s statement and do not apply this property for their measure. However, we do not agree with their statements. In the original Chidamber et al. paper [33], the authors argued that this property is not useful in calculating the complexity of a class because the order of statements within the class is not important in calculating the complexity. However, in our opinion, if the class complexity is calculated by adding the method complexities (since the order of statements are important in this case) it is a challenge to neglect this property. However, one should be careful when using this property. This is also the reason why WCC does not satisfy this property. Although, Chidamber and Kemerer [33] suggest that it is not a useful property for OO metrics, from our point of view it is a useful measure for evaluating OO metrics.

Property 8: If P is renaming of Q, then $|P| = |Q|$

This property requires that when the name of the class or object changes it will not affect the complexity of the class. Even if the name of the member function or member data in the class changes, the class complexity should remain unchanged. All complexity measures in Table 1 satisfy this property. Since the complexity is not affected by renaming, it is not a meaningful property for any OO metric.

Property 9: (∃P) (∃Q) (| P |+| Q |).< (| P; Q |)

This property states that interaction increases complexity. This property states that the class complexity of a new class combined from two classes is greater than the sum of the complexities of its components. In other words, when two classes are combined, the interaction between the classes can increase the complexity metric value. Due to this reason, most of the complexity measures do not satisfy this property. Again, the developers of NCBC and EMF [35] have not made use of this property by saying that this property is not applicable for OO measure, as stated by Chidamber et al. [33]. Again, we do not support their statement; no such type of indication in the original paper of Chidamber et al. [33] has been found, and it has been argued that this property may not be an essential feature of OO software design. It appears only as a suggestion and they themselves have used this property for evaluating all their measures. Further, the usefulness of this property for OO metrics has been discussed and proved by several researchers, and it remains a topic of research. [19-21]. The author of the present paper has also proposed a modification in this property [24]. This proposal was basically for procedural languages, but we check its applicability to OO measures in this paper.

Conclusion of the Evaluation of Weyuker's properties: Weyuker's first, second, third, fourth, sixth and eighth properties are satisfied by all complexity measures. It is because of the fact that most of the properties are general in nature and hence can be satisfied by any complexity measure. Furthermore, the observation shows that only six properties [25] are useful for OO metrics. However, in these properties, there is no orientation towards OO languages and metrics. Most of the important properties, such as property 5, 6, and 9, are based on the principles of measurement theory. Once we evaluate the proposed metric with the principles of measurement theory, it is automatically satisfied by Weyuker's properties. Additionally, we have observed that Weyuker's properties do not address language independency [24], which a complexity measure should account for; i.e. a complexity measure should be language-independent. This property has been proved as an essential feature for procedural language. Let us evaluate this property for its applicability to object-oriented metrics.

2.2 Evaluation of the Applicability of Measurement Theory to OO Metrics

The evaluation of complexity measures via measurement theory is established by several researchers [2, 6-10, 15, 17, 18]. However, proper applicability of these measures to OO metrics is not evaluated properly except by a few [15]. If we review the literature to find the relation between evaluation criteria for software complexity metrics and measurement theory, we can find three important proposals: Briand, Morasca, and Basili's [2] 'property based software engineering measurement', Kitchenham, Pfleeger, & Fenton's [6] proposal on 'towards a framework for software measurement validation' and Zuse's proposal for software

measurement [15, 17]. Although many other proposals based on measurement theory are available in the literature, most of them are either related to these three, in developing stages [8] or not used by the software community [7]. In the following paragraph, we will see how effective these different theoretical evaluation criteria are in evaluating OO measures.

Amongst available validation criteria, the framework given by Briand, Morasca and Basili [2] is used by several researchers [38-40]. Briand, Morasca and Basili [2] have proposed measurement properties of various measurement concepts, such as size, length, complexity, cohesion and coupling. The authors have tried to make the differences in these different measurement concepts by proposing a set of properties. For calculating the complexity of a system, they proposed five properties, which include nonnegative (Complexity property 1), null value (Complexity property 2), symmetry (Complexity property 3), module monotonicity (Complexity property 4) and disjoint module additive (Complexity property 5). The first property states that the complexity of a system should not be a negative value. The second property states that if a system has no elements, then its complexity value should be zero. The third property states that the complexity of a system should not depend on the convention chosen to represent the relationships between its elements. The forth property states that complexity of a system should be no less than the sum of the complexities of any two of its modules with no relationships in common. The fifth property states that the complexity of a system composed of two disjoint modules is equal to the sum of the complexities of the two modules. The fourth and fifth properties are related to the additive nature of the metric. Furthermore, by satisfying all these properties (Complexity.1 – Complexity.5), the measure will be on the ratio scale. It is important to note that the first three properties are common in other measures also, i.e. for length and size. In summary, by satisfying these properties by complexity measures, it proves the ratio scale and additive nature of the measures.

The second method to evaluate complexity measures is through representation conditions [4, 6]. To satisfy the representation conditions, initially there should be an empirical relation system (ERS), numerical relation systems (NRS), and a complexity metric, which is defined as the mapping between ERS to NRS. Furthermore, a measure/metrics must be satisfied by the two conditions called representation conditions. The first part of the representation condition says that any empirical observation should be measurable and any measurement result should be empirically observable. The second part says that the complexity of the whole should be definable in terms of the complexities of its parts. Again, the conclusion of the representation condition states that the measure should be additive.

Zuse [15] has introduced properties of OO software measures. This is the only work which especially emphasizes the properties of OO metrics. In this work, Zuse has proved that OO metrics do not assume an extensive structure and hence he has proposed some new measurement principles for OO metrics. He used terms

such as the Dempster-Shafer Function of Belief, the Kolmogoroff axioms and DeFinetti axioms. However, it is a common observation that these theories for OOM evaluation have neither been applied nor have they been used by most of the developers of OO metrics.

The scale measurement is also an important issue for evaluating software complexity metrics and proved by several researchers. The third evaluation method which is normally applied to the complexity measures is to investigate the scale of the measure [17]. In fact, it is not easy to separate scale measurement with the first two methods, but there are also different ways to achieve the scale. There are two ways for scale measurement in software complexity measurement: admissible transformation and extensive structure [17]. It is assumed that a complexity measure should be on ratio scale. We have included the scale measurement in our model.

Conclusion for the Applicability of Measurement Theory: In all of the above measurement criteria applied for evaluation of software complexity measurements, all of them recommend that the measure should be additive, hence on ratio scale. The way of achieving this goal may be different; for example through admissible transformation, extensive structure or representation condition, but the goal of all aforementioned criteria is the same, i.e. to achieve ratio scale.

By keeping this issue in mind, in the following paragraphs we evaluate the additive nature of the existing object-oriented measures. Based on the evaluation, we will discuss the applicability and relevance of measurement theory to OO measures.

2.3 Additive Property and Language Independency of OO Measures

Based on the observation in Sections 2.1 and 2.2, we observed two important points:

1) From measurement theory perspective, all of the different criteria suggest that a measure should be additive. The additive property is not directly addressed by Weyuker's.
2) In addition, Weyuker does not discuss anything regarding the language independency of a proposed measure.

Following the above mentioned points, we evaluate the applicability of additive property and language independency to OO metrics.

a) Additive Property

The additive nature of the complexity measure is proved as one of the desirable properties from measurement theory perspective. Misra [24] has presented the additive property in mathematical form. In fact this property was suggested by

several researchers and in [24], the author has suggested modifying Weyuker's property 9. First, we explain this property [24] and later we check all the considered OO complexity metrics against this property.

Property 1: $(\forall P)\,(\forall Q)\,(|\,P;\,Q\,|) \geq |\,P\,| + |\,Q\,|$.

This property states that the complexity of a program ($|\,P;\,Q|$) composed of two components cannot be less than the sum of the complexities of its component bodies.

In fact, this property is not a new one but rather a modified version of Weyuker property 9. Weyuker herself rejected this property, arguing that the effort needed to implement or understand the composition of a program body P with itself is probably not twice as much as the effort needed for P alone. However, it seems reasonable that the complexity of a program body can be related to the complexity of all of its parts. That is to say, it is necessary requirement for any complexity measure. The additive nature is also related to the scale of the measure [41]; that is to say, if any measure is additive, then it is also assumed to be on ratio scale.

b) Language Independency Property

Misra has [24] observed that Weyuker's properties do not address language independency, which a complexity measure should account for; i.e. a complexity measure should be language-independent. The author has presented this property as;

Property 2: $(\exists P)(\exists Q)(\exists R)(P \equiv Q \equiv R \,\&\, |\,P\,| = |\,Q\,| = |\,R\,|)$**; Where P, Q, and R are the classes written in different languages**

This property states that if P, Q, and R are the classes for the same algorithm in a different programming language, then the complexity should be the same. In other words, this property states that a measure should rank the complexity of the same algorithm in a different language as equally complex.

Now the applicability of these properties is checked against the OO metrics under consideration.

c) Applicability of language Independency and Additive Properties to OO Metrics

Weighted method per class (WMC). If WMC is calculated only by counting the number of methods, (In [33] the authors have suggested taking the weight of each method as 1 unit.) the language independent property is satisfied by this measure. This is because the numbers of methods for classes in different languages are assumed to be the same. In this respect, this property is satisfied by this measure. On the other hand, if we calculate the complexity of the each method independently, by any procedural metric, it depends on the characteristics of the applied procedural metric.

For the additive nature of WMC, if we combine two classes, it is possible that the number of methods in the combined class may reduce in comparison to the sum of the methods of independent classes because there may be some methods in both classes. As a result, WMC is not an additive measure.

Depth of inheritance tree (DIT) is satisfied by the language independent property because the tree structure for the same problem is assumed to be same for all object-oriented languages.

DIT is not an additive measure because when we combine the two classes, the DIT value of the resultant class will not be the sum of the DIT values of the independent classes. It is because of the fact that when two OO programs with multiple hierarchies combine with each other, they combine in parallel way. This is to say, if DIT value of two OO programs are 3 and 2, then it is not equal to 5 for the combined class.

Number of children (NOC) also satisfies the language-independent property. A similar argument for DIT is applicable to NOC.

NOC does not satisfy the additive property due to similar arguments to those given above (for DIT).

Coupling between object (CBO) also satisfies the language-independent property because it depends on the number of messages through which the classes are coupled.

The numbers of message calls will not change by a change in the language.

CBO is the measure which depends on the number of message calls to the other classes. If we combine two classes, in which one of them has a message call for the other class, then naturally, after combining these classes, there is no coupling in the combined class. In this respect, CBO also does not satisfy the additive property.

Response for the Class (RFC) is defined as the total number of methods that can be executed in response to a message to a class. This count includes all the methods available in the class hierarchy. Since class hierarchy is the same for all languages, RFC satisfies the language-independent property.

RFC also does not satisfy the additive property because after the combination of two classes, the total number of methods that can be executed in response to a message to a class will not be the sum of the total number of called messages of two independent classes.

Lack of cohesion in method (LCOM), which is related to the counting of methods using common attributes, does not satisfy the language-independent property. This is because the use of attributes inside the methods depends on the programming language.

LCOM does not satisfy the additive property. This is because the use of attributes inside the methods depends on the programming language and on the fact that, when we combine two classes, the number of methods using the common attributes of the independent class will not be the sum of the combined class.

Complexity measure for OO program based on entropy (CMBOE) is a measure based on entropy. The entropy of an OO program is computed on a per-class basis dependent on the name strings, methods, messages, and their architecture. For a given problem, the different OO languages may have different representation of the classes and its contents, and therefore the entropy of the same problem in different OO languages may be different. From this point of view, CMBOE does not satisfy the language independency.

CMBOE is not satisfied by the additive property. In the original paper [34] the authors have proved that the complexity of the combined class is greater than the sum of the complexities of independent ones.

Component complexity (CC) is based on classes, methods, attributes and interfaces. The authors [36] have used the coefficients for classes, methods and attributes, which are dependent on the nature of the component-this means on the nature of programming language. As a result, CC does not satisfy language-independent properties.

CC does not satisfy the additive property because it is based on classes, methods, attributes, and interfaces. Once we combine the two classes, and if there are some common methods and attributes in both, then the complexity of the combined class reduces.

Number of Catch Blocks per Class (NCBC) is defined as the ratio of catch block in a class (the sum of the catch blocks of each method) to the total number of possible catch blocks in a class [35]. Since NCBC depends on the internal architecture of the method, which varies from language to language, NCBC does not satisfy the language independency.

NCBC does not satisfy the additive property because it depends on the sum of the catch blocks of each method, and methods may be common in both classes, which reduces the complexity of the combined class.

Weighted Class Complexity (WCC) depends on the attributes and the internal architecture of the methods, which are not same for all programming languages. From this point of view, WCC is not a language-independent complexity measure.

WCC does not satisfy the additive property. It depends on the attributes and the internal architecture of the methods. After combining the two classes, their number may reduce due to the common methods and attributes.

Exception-Handling Factor (EHF) is defined as the ratio of the number of exception classes to the total number of possible exception classes in software. EHF depends on the classes, which should be the same for all programming languages. As a result, EHF satisfies the language independency.

EHF does not satisfy via the additive property because the number of exception classes is the count of the exceptions covered in a system [35]. If we combine the two classes, the EMF values do not combine with each other due to the nature of the metric; EMF is also not an additive measure.

The applicability of language independency and the additive property by different complexity measures are summarized in Table 2.

Table 2
Language independency and additive properties of OO languages

Properties ---------- Metrics	Language Independency	Additive Nature
WMC	Y	N
DIT	Y	N
NOC	Y	N
CBO	Y	N
RFC	Y	N
LCOM	N	N
CMBOE	N	N
CC	N	N
NCBC	N	N
WCC	N	N
EMF	Y	N

From Table [2], we can easily observe that none of the OO metrics are additive in nature, which is not compatible with the principles of measurement theory. All the three proposals in measurement theory strongly suggest that a measure should be additive in nature [2, 6 and 17]. However, our experiments show the negative results and prove that OO measures do not satisfy the additive property. For the language independencies of OO metrics, we have found a mixed response. Six out of eleven OO metrics are language independent measures. Also language independency is a reasonable requirement for any metric hence OO metrics.

Based on the evaluation measurement theory, scale measurement, language independency, additive property, and Weyuker's properties, we propose our model in next section.

3 Proposed Evaluation Criteria/ Model

The proposed validation and evaluation criteria have the following four stages:

1 Identifying the basic requirement for proposing OO measure

2 Evaluation through the measurement theory and Scale measurements.

3 Empirical Validation

4 Identifications of Thresholds and limitations

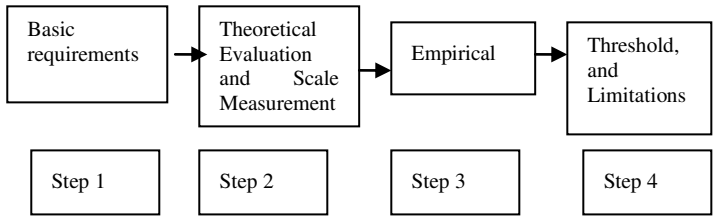

Figure 1
Proposed model for evaluation of OO metrics

3.1 Identifying the Basic Requirement for OO Measure

Based on the properties suggested by different scientists, the following set of simpler and essential properties is summarized, against which an OO measure/metric should be evaluated For this purpose, studies by Kitchenham, Pfleeger, & Fenton's [6], Linda [14] and Morasca [18] are used to extract these features and present them in a formal way.

1) Identifying the OO features under investigation.

- The first step in proposing an OO metric is to decide what to measure. It is important that a metric or measure evaluates one of the following features of OO: methods, classes, cohesion, coupling, inheritance, information hiding, and polymorphism.
- An OO metric should focus on an internal object structure.
- An OO metric should measure the efficiency of an algorithm and the use of machine resources.
- An OO metric should evaluate the psychological measures that affect a programmer's ability to create, comprehend, modify, and maintain software.

All of our metrics under consideration are specific to OO features. For example, WMC is related to the internal architecture of method and class, DIT with inheritance, NOC also with inheritance, CBO with coupling, RFC with class, LCOM with cohesion, CC, NCBC WCC,EHF and CMBOE with class.

2) Identifying the quality factors/attributes

The attribute(s) under investigation by the proposed OO metric should be identified in the beginning. If the metric or suite of metrics is capable of

evaluating more than one of the attributes (also called quality factors), then they should be priorities. Some of the attributes are:

Performance

Reliability

Maintainability

Portability

Efficiency

Understandability

Reusability

Testability

A number of developers of complexity measures do not care for this part. Although one can guess the attributes under investigation from their original papers, in most papers this part is not clearly defined. For example, in the original proposal of NCBC and EHF, nowhere in the entire paper is it discussed for which attributes they are proposing metrics. They stated that two metrics were developed to measure the amount of robustness included in the code. It can be guessed that NCBC and EHF are representative of maintainability. The attributes measured by other metrics are: maintainability by WMC, DIT, NOC, CBO, RFC, LCOM and CMBOE, and understandability, maintainability and reliability by WCC.

3) A basis for the proposal of a new metric should be developed

The foundation for the metric development should be built. It should include the literature survey, motivations, comparison and quality references which will prove the worth and need for a new proposal. Based on discussions of related work published, it should be clearly explained why it is important and how much the new metric will add to the field. Furthermore, a clear-cut proposal for the system should be developed, and the way, method or instrument by which it is to be measured should also be identified. Also the relationship between attribute and metric should be determined.

Although most of the metrics under consideration have been clearly defined in their original papers, one can easily find a number of metrics in literature that were developed without a clear-cut purpose and aim.

3.2 Theoretical Evaluation and Scale Measurement

A metric and the prediction system are acceptable only when their usefulness has been proved by a theoretical validation process; otherwise it may mislead its users. In Section 2.2, we observed that the conclusion of most of the validation criteria based on measurement theory is related to the additive property of the measure.

However, most of the OO metrics under experimentation are not additive in nature. This result forces us to rethink the applicability of measurement theory to OO metrics. According to our point of view, we should not neglect the principles of measurement theory; instead, we should concentrate on some basic requirements and important features (from the measurement theory perspective) which are required to form the scientific basis of the metric. The next important issue in terms of measurement theory is the scale measurement of the proposed measure. Keeping this issue in mind, we propose simple and important features required by measurement theory and the investigation of the scale measurement.

From the measurement theory point of view, there should be an entity, a property and measurement mapping. The measurement mapping and rules are called metric [18].

1) Entity: An entity is an object or an event in reality. For example, the entity for all the OO metrics under consideration is class.

2) Property: The property of the class which is under investigation is different for different measures. For WMC, CC and the WCC the property is the complexity, for DIT, NOC, RFC and CBO the property is coupling, for LCOM the property is cohesion. The property for NCBC and EMF is complexity.

3) Metric: Metrics should be defined by a function(s) which assigns a value to the attribute. All the metrics under consideration are properly defined in their original papers. Although some of them, such as NCBC and EHF, do not map their values to attributes, their definitions are clear.

4) Attributes: An attribute is a feature or property of an entity. Furthermore, the attributes can be classified as internal and external attributes [42].

4.1) Internal Attributes: Internal attributes are those which can be measured purely in terms of the product, process or resources [42]. Since the entity for all the metrics under consideration is class, then we can examine the attributes which are related to class.

The internal attributes for the class may be the size in terms of the number of lines of code, the number of methods, the number of attributes/variables, coupling in terms of the number of message calls to other classes, and cohesion in terms of the number of common attributes used in different methods of the same class. The internal attributes for the considered OO metrics are summarized in Table 3.

4.2) The external attributes: External attributes are those which relate the product, process or resources with the external environment. For example, for object-oriented measures, the external attributes are reliability, maintainability, usability, and understandability. The external attributes of all the metrics under consideration are also summarized in Table 3.

Evaluation of Measure based on Scale

After the identifying entity, attributes and defining the metric, one must investigate the type of scale. Normally, there are five different types of scales: absolute, ratio, interval, ordinal and nominal. The definitions of all these scales are given in brief [17]:

1 Nominal Scale: any one to one

2 Ordinal scale: g: strictly increasing functions

3 Interval scale: $g(x)= ax+b$, $a> 0$

4 Ratio Scale: $g(x)= ax$, $a> 0$

5 Absolute Scale: $g(x) = x$.

These scales are classified according to admissible transformations [17].

The scale of most of the complexity measures under consideration are not evaluated in their original paper, except WCC. The scale for CK metric suites were evaluated in [43, 44]. The possible scale for all the complexity metrics are summarized in Table 3.

It is worth mentioning here that most of the OO metrics are not additive in nature. This is also because they do not satisfy the extensive structure [17]. In other words, most of the OO metrics are either on an interval or ordinal scale. The scale of all the OO measures under investigation is given in Table 3.

Table 3
Attributes and type of scale for Different measures

	Metrics ---------- Attributes For entity class	WMC	DIT	NOC	CBO	RFC	LCOM	WCC	CMBOE	CC	NCBC	EMF
Internal Attributes:	Size	N	Y	Y	N	N	N	Y	N	Y	N	N
	reuse	N	Y	Y	Y	N	Y	Y	N	N	N	N
	coupling	N	Y	Y	Y	Y	N	Y	N	Y	N	N
	cohesiveness	N	N	N	N	N	Y	Y	N	N	N	N
	Functionality	Y	N	N	Y	N	N	N	N	Y	Y	
External Attributes:	Maintainability	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	reliability	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	usability	N	Y	Y	Y	N	Y	Y	N	N	N	N
	Understandability	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Scale		Ns	Ns	Is	Is	0s	Is	Ns	Is	Is	Ns	Is

Y: Yes, N: No, In last row, Ns: Nominal Scale, Is: Interval Scale, Os: ordinary scale

3.3 Empirical Validation

Several researchers [45-48] have pointed out the importance of empirical validation for software metrics. It is the way through which the academician and scientist can assist industry in selecting new technology. On the other hand, it is a common observation that the standard of empirical validations for software metrics is not up to the required level [45]. There is no match in content between the increased level of metrics activity in academia and industry [49]. This is because of the fact that there is no direct link between researchers and industry, and this makes it difficult to validate the metrics against real projects. As a consequence, researchers try to validate their metrics through other means, such as experimentations in labs, classrooms or the available data/programs from the internet. Most of the time, they fulfill only partial empirical validation. However, for complete empirical validation, one must apply the new technology/metric to real data/projects from industry.

Considering the above pitfalls, we have suggested the application of empirical validation in two stages [27]. The first stage of empirical validation includes the initial validation of the metrics by applying them to different test cases and examples. In the second stage of the empirical validation, the new metric is tested by using real projects from the industry. The details of all the steps of the empirical validation process are discussed in [27]. In the following paragraphs we provide them in abstract form.

The first stage of the empirical validation includes the case study, applying it to a small project available on the web or in literature. In this stage, the proposed metrics can be validated through experimentations in labs, classrooms or the available data/programs from the internet. In parallel, similar metrics should also be applied to all these different ways of validation. This will be helpful for comparative study and finally in proving the usefulness of the proposed metrics.

The complexity measures under consideration, WMC, CC, WCC, DIT, NOC, RFC, CBO, LCOM, NCBC and EMF, have undergone these initial phases validation. One should bear in mind that the initial validation is not a guarantee of success or of the usefulness of the proposed metric without the second stage of validation.

The second stage of the empirical validation proves the actual applicability of the proposed metric. This stage of validation is a must, and it evaluates the validity of the metric by applying it to a real project from industry. The difference between the first and second stage is that, in first stage, the examples/case studies may be small in size and collected from literature and web; in the second stage, the examples/case studies are real data from industry. As in the first stage, similar metrics should also be applied to the real project(s), for comparative purposes. In fact, the second stage of empirical validation is the real proof for a new measure.

We recommend the first stage only in the cases when the data from the industry is not immediately available.

For the metrics under examination, with the exception of the CK metric suites, none of the metrics have been applied to real projects from industry. This is also the reason that none of them, again with the exception of the CK metric suites, are very popular and accepted in industry.

3.4 Thresholds for the Metrics should be Identified

After preliminary and advanced empirical validations, the thresholds for the metrics should be developed. Although it is possible to propose the thresholds for a new metric before empirical validations, empirical validations can change the threshold values. This is because of the fact that, after the analysis of the results obtained from a real project, the developer can change their thresholds. Furthermore, the initial proposal only gives the basic idea of the proposed measure, which may fail in real life applications. This is one of the reasons for the lack of acceptance of the majority of OO metrics from the industry which are available in the literature.

The importance of thresholds is discussed by several researchers. Lorenz and Kidd defined threshold as [50] "heuristic values used to set ranges of desirable and undesirable metric values for measured software. These thresholds are used to identify anomalies, which may or may not be an actual problem." Henderson-Sellers [51] states the importance of thresholds as, "An alarm would occur whenever the value of a specific internal metric exceeded some predetermined threshold." In fact, threshold values are the best indicator for the rating of the complexity values for an OO system. For example, in WMC measurement, if the number of methods for a class exceeds 100 (the weight of each method is assumed to be 1), then this class automatically becomes more error-prone and less understandable, which also increases the maintenance efforts. Also, the importance of thresholds is supported by cognitive theory [52, 53]. The authors in [52, 53] use a human memory model and suggest that more complex classes will overflow short term memory, which results in more errors. Contrary to these results, some of the authors presented some experimental results which show that there is no impact of threshold values on the fault tolerance. There is a continuous relationship between measures and fault tolerance and errors [28]. However, in our opinion, for any new model or theory, contradictory cases exist. Threshold values are only indicators and act as an alarm which tells you that over this limit there is a high chance of errors. It is possible that one can build a system whose complexity values cross the threshold values and is nevertheless error free.

If we evaluate our metrics under consideration, we observe that most developers do not propose thresholds values. In particular, for the CK metric suite, the authors gave some hints of these numbers but did not clearly define the threshold values.

For example, they observed that the maximum values of DIT were 10 or less. This value was observed based on the empirical validation study. Later, due to the high popularity and acceptance of Chidamber et al.'s metrics, the thresholds were investigated by other authors [54]. The threshold for WMC is 100, the inheritance nesting level (another form of DIT and NOC) is 6 [50]), for CBO it is 5, and for RFC 100. For other metrics, WCC, NCBC, EMF and CMBOE, no threshold values were investigated. If no threshold is defined, how can one guess with numbers whether these numbers are either a good or bad predictor of complexity?

Further, there exist limitations and boundaries in a new proposal. It is not easy for a single metric to evaluate all the aspects/attributes of code. From our point of view, the limitations of new measurers can best be described by the developers. Some of the examples include: Are the metrics applicable to the design phase or also applicable to the testing phases? For example, most of the metrics in the CK metrics suite are fit for the design phase; however, WCC is fit for both the design and testing phases. WCC can be applicable in the design phase to reduce the class complexity by limiting the number of complex methods; and in the testing phases it can be applied to reduce bugs. Another example of the limitation is: Can one evaluate the complexity only by simple calculations, or does it require software, and if this is the case, is it then available? If not, the chances for practical use of the proposed metric immediately decrease. It can be easily observed in a number of metrics that they have proved their worth for small codes and examples, but it is not easy for them to fit in the real environment of software developments, where codes are quite large and distributed in different classes and in different files. Also the developer should provide the range of values which gives an indication of the different levels of quality attributes.

4 Observations

We observe the following points in this study:

1 There are no models/frameworks/proposals which state clear-cut guidelines for the properties of object-oriented measures.

2 We have proved that the existing criteria, such as Weyuker's properties and measurement theory, are as such not fit for evaluating OO metrics.

3 It is clear from Table 1 that Weyuker's first, second, third, fourth, sixth and eighth properties are satisfied by all given complexity measures. Weyuker's first property states that no complexity measure can rank all classes as equally complex. Since the universe of discourse deals with a finite set of applications, each of which has at most a finite number of classes, property two will be satisfied by any complexity measure at the class level. Weyuker's second and third properties give the same conclusion.

Weyuker's eighth property is concerned with the name of the class, which does not affect the complexity of any class. In conclusion, Weyuker's first, second, and eighth properties are found to be not useful for the evaluation of complexity measures for OO programming. Other properties are compatible with measurement principles.

4 Weyuker's properties number 3, 5, 6, 7 and 9 are found useful for evaluating OO metrics. On the other hand, all these properties are compatible with measurement principles. If we evaluate our measure through the fundamentals of measurement theory, then we have no need to apply Weyuker's properties. This is the reason that we have included only evaluation via measurement theory, and not via Weyuker's properties.

5 All of the different criteria based on measurement theory recommend that a measure (in general) should be additive; it hence should be on a ratio scale. Weyuker's modified property nine [24] is also a representation of the additive nature of a measure.

6 None of the OO metrics under consideration are found to be additive in nature.

7 No complexity metrics under consideration are on a ratio scale according to measurement theory principles.

8 Further, the existing validation criteria/properties for OO metrics based on measurement theory by Zuse [15], are difficult to understand and hence not easy to apply to OO metrics. The theory requires a sound knowledge of mathematics. This is the reason that most of the proposed OO metrics do not follow these properties.

9 Other measurement criteria, such as representation condition, also do not provide too much information (such as ratio scale and additive nature) for OO measures.

All of these observations indicate that theoretical evaluation of an OO metric through the representation condition [4, 42], extensive structure [15, 17], and complexity property [2] are not effective for evaluating OO metrics. In this respect, the fundamental properties and definitions required by measurement theory should only be the necessary condition for OO metrics, which we summarized in Section 3.1. Furthermore, in the case of software engineering, empirical validation is more important than theoretical validation, and if a metric is properly validated empirically, via data from industry, and evaluated through the given fundamental definition from measurement theory, it proves the worth of the measure. It is also worth mentioning that, although empirical validation is the most important part of the validation process, it does not mean that theoretical validation should be ignored. Theoretical validation proves that the metric is developed according to certain rules and regulations and based on principles of measurement theory.

Conclusion and Future Work

The necessity of evaluation and validation criteria for object-oriented metrics is clear. However, in assessing the existing evaluation criteria, we have observed that most of them consider only specific features for the evaluation of a metric, and, especially, they are not proposed in keeping with the special features of OO metrics. For example, Weyuker's properties only cover the mathematical features of programs (for procedural languages) and do not evaluate any practical aspects of the metric. So Weyuker's properties are not suitable criteria for the theoretical evaluation if applied independently. Further, measurement theory also includes most of the features of Weyuker's properties; so if a measure is evaluated via measurement theory, then Weyuker's properties can be avoided. On the other hand, additive nature and ratio scale are two main requirements for a measure from a measurement theory point of view; however, both are rejected by the majority of OO metrics. This is a constraint in the application of the principles of measurement theory to OO metrics. Further, the original measurement principles proposed by Zuse [9] are difficult to understand. Additionally, the empirical validation process is also not clearly mentioned in the literature. All these issues indicate a need for a unified model, which should be simple to apply, and which should cover the majority of the features required for the evaluation and validation of OO metrics. The presented model is an attempt to achieve this goal in this area. We kept all these issues in our mind before constructing our model. We have proposed a simple four-step model against which a software complexity measure for OO metric should be evaluated. Our first step is to prepare the basis of the proposal. The second step is related to theoretical validation, which includes the principles of measurement theory in a simple way. These first two steps form the scientific basis for proposing a new OO metric. Our third step is related to empirical validation, which is proposed in two steps. The final step is to provide thresholds for the proposed metrics based on real observations, which is intended to provide valuable information regarding the actual analysis of metric values. In fact, it is not easy to achieve completeness through independent existing evaluation criterion. This became a motivation for us to propose a unified model. We hope that our attempt will make a valuable contribution to practitioners and as well to academicians who have the intention of proposing a new metric in the OO environment.

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Analysing the Colours of the Virtual Reality Museums' Picture

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Abstract: Showing the works of famous artists to students is a fundamental task in order to teach fine art history. Images found on the Internet are a major source for such pictures that can replace older albums of fine art collections. The question arises as to how far one can rely on the colour quality of the images displayed on the Internet, and as to whether it is worthwhile to put much effort into the colour correct presentation on the receiving side. Images have been collected both from museums' publications and from the Internet, and some critical areas of the images have been colorimetrically evaluated. From these comparisons one can conclude that at present the distributors of the images do not pay enough attention to putting colour-correct images onto the Internet.

Keywords: colour; virtual reality; museum

1 Introduction

1.1 Background

Teaching fine art history without showing the masterpieces of past centuries is difficult. Unfortunately, it is impossible to take classes to all the major museums around the world to show the originals of the masterpieces to the students. Some fifty years ago, the art teacher had to rely on printed books of reproductions and had to use an epidiascope to show the pictures in the class. Then came the time of slides, and one was happy with the better colour quality of these. But slides fade, and after about ten years the colours become distorted. In recent years digital storage and reproduction via highly sophisticated projectors have become available, and one would hope that with proper colour management the perceived colours of the originals could be shown.

At the same time museums have started to archive the artifacts of their masterpieces in digital form, and more and more images are becoming available on the Internet. The pictures of the original images are taken by experts using

sophisticated high-end camera systems and illumination equipment to provide artefacts where the colours come near to the original ones [1]. Colour characterization of high-end digital cameras can yield digital images that hold most of the features of the original [2]. Digital restoration techniques can even help in rejuvenating faded paintings [3]. The recent technique of multi- (or hyper-) spectral image taking provides the opportunity to consider the reflectance spectra of the pigments the artist used [4]. This enables even transformations when looking at the pictures under different illuminants.

Despite all that hard work, the artefacts reproduced on the Internet often show remarkable differences if downloaded from different databases. In the present study, our main endeavour is to show the size of the colour differences one has to count on in reality.

As we will see, to take full advantage of present-day colorimetric capabilities, the providers of digital museum artefacts should supply more detailed metadata information, because otherwise, any further work by the user is only guess-work.

1.2 Colorimetric Fundamentals and Measurements

Pictures on the Internet are most often encoded using the IEC recommended sRGB encoding [5]; for further details and other encodings see e.g. [6], [7]. This encoding assumes standard RGB primaries (standardized RGB phosphors of CRT monitors) and a standard light intensity – digital value interrelationship, the so called gamma curve.

As every camera and every piece of reproducing equipment (monitor, projector, printer) have different encodings, it is usual to transform from the native colour space into a device independent colour space, the CIE recommended XYZ or L^*, a^*, b^* (or CIELAB) space [8], [9]. The latter one has the advantage that it provides reasonably uniform colour scales in lightness (L^*) and chroma (C_{ab}^*) and gives more or less equidistant scaling along the hue circle (h_{ab}^*). Figure 1 shows the co-ordinates of the CIELAB colour space.

The L^* coordinate goes from black ($L^* = 0$) to white $L^* = 100$), the positive a^* axis shows approximately into the red direction, the negative into the green direction, positive b^* represents yellow, negative b^* blue.

The h_{ab}^* hue angle is constructed as the arc tangent of b^*/a^*. Thus orange colours have arctg(b^*/a^*) values between 0° and 90°. Colours ranging in hue between yellow and green have hue angles between 90° and 180°, those between green and blue range between 180° and 270°, while purple colours might have hue angles between 270° and 360°.

The C_{ab}^* CIE chroma describes how vivid the colour is; colours with small chroma values are pale, greyish hues; strong, vivid hues have high chroma values.

In the evaluation of the different artefacts the L^* lightness value, the a^* and b^* co-ordinates, and also the h_{ab}^* hue-angle and the C_{ab}^* chroma information will be provided. Colour differences in these colour co-ordinates are: just noticeable if the colour differences as Euclidian distance between the L^*, a^*, b^* co-ordinates (ΔE^*)of the two colours to be compared are of the order of one to two units. Rich and co-workers [10] reported on the possibility of simulating surface colours on a CRT monitor within a $\Delta E_{ab}^* = 5$ range, although they admit that the usual reproduction differences are in the 6 to 12 ΔE_{ab}^* units range.

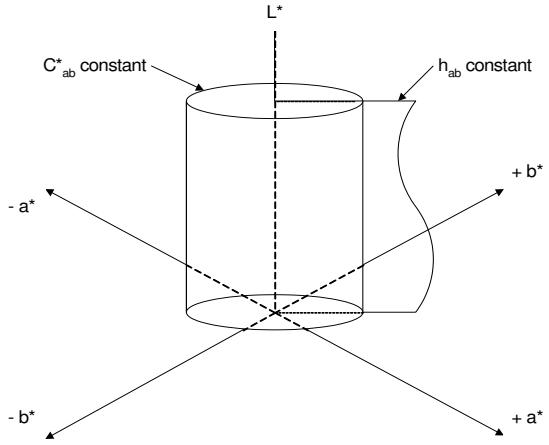

Figure 1
Coordinates of the CIE L^*, a^*, b^* colour system, called also CIELAB space

Measurements were performed partly using a Gretag Macbeth i1 spectrophotometer with a BabelColor software extension[1], partly – for some of the Internet artefacts – by loading the pictures into Adobe Potoshop®, using the eye-drop facility of the program and setting the colour management of the Photoshop to sRGB.

2 Examples of Colour Differences of Artefacts of the Same Pictures in Different Databases

The following examples are a non-exhaustive sample of a few pictures where artefacts of the same picture from different databases were found. Our intention was to show how large colour differences might be found on the Internet. In some cases we compared these with printed copies of the given picture as well. We have

[1] Thanks are due to Dr. Danny Pascale for helping our work with this software.

to stress that this investigation was conducted only on digital and printed artefacts, and we had no access to the original paintings, thus we had no information on the colour difference of one or the other artefact compared with the original.

2.1 Four Paintings by Leonardo da Vinci

As is well-known, Leonardo made at least two versions of the subject "Madonna/Virgin of the Rocks". The first one is a picture kept in the Louvre, Paris, and the latter one is in the National Gallery, London. As the subject of both paintings are very similar, it seemed to be worth not only investigating how different the coloration of the reproductions of these paintings is found in different databases (museum albums will from here on be included in the term "database"), but also worth checking how large differences could be found of the same object in the two versions, painted some decades apart. This can give an insight into the colour memory [11] of the painter and give us some hint how important he thought the colour of a given object was. This can be especially important for human skin tones, as we are often very critical as regards the reproduction of skin tones, as well as the blue of the robe of the Madonna (as this blue had heraldic information too).

Seven artefacts shown on the Internet of the subject have been analysed; four of them were reproductions of the Louvre version [12]-[14], and two of the National Gallery version [12], [14], [15]. Further, two printed versions of the Louvre and one of the National Gallery versions were included in our investigation.

Figure 2 shows the example of the Louvre version, with three areas of skin tones (the forehead of the Madonna and of the angle and the leg of St. John) marked with a white circle. As second hue, the blue of the robe of the Madonna was selected, a portion on her shoulder in the Louvre version and on the breast on the National Gallery version. Also, these areas are shown in the picture by small circles. These are areas that could also be easily identified on the London version of the picture. Further versions were selected from museum albums [16]-[18] where some parts of the pictures were enlarged and could be measured with higher accuracy.

Table 1 shows the L^*, a^*, b^* values measured for the three selected skin tones and the portion of the robe, measured on the artefacts from different databases of the Louvre version of the picture.

Similar measurements were made on artefacts of the London version of the painting. For this we show in Table 2 data, from different databases, for the forehead of the Madonna, as this is a critical skin tone. As can be seen, we got only in one case a pale yellowish colour ($h_{ab}^* \approx 60°$); in two other cases reddish hues were obtained ($h_{ab}^* \approx 0°$).

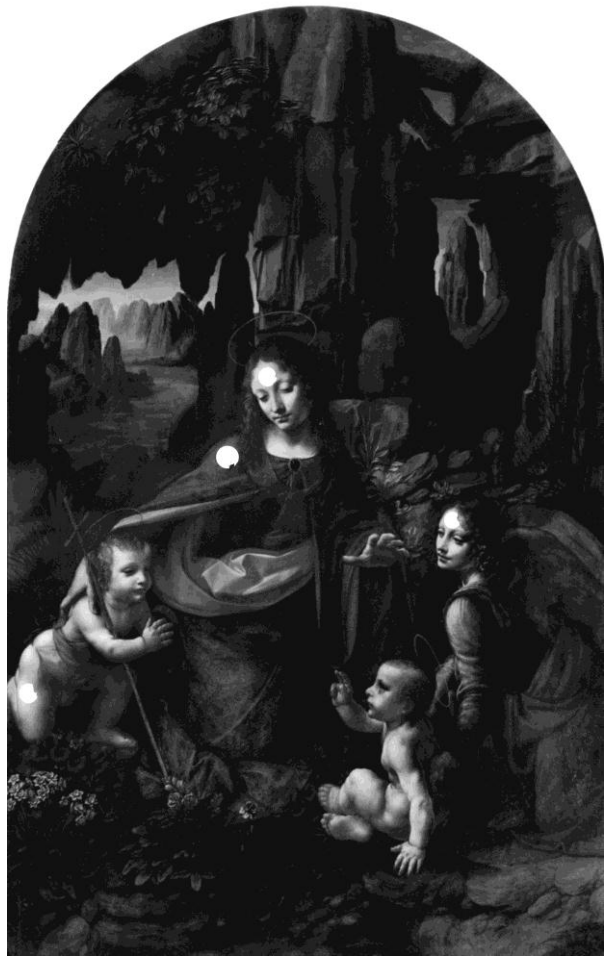

Figure 2
Black and white reproduction of the Virgin of the Rocks picture, showing the four parts were colour measurement was made.

Table 1
Average skin tones, colour of the robe of Maria and their standard deviations (in brackets) for four parts of the Madonna of the Rocks (Louvre) painting using the Photoshop eye-drop tool, based on seven Internet reproductions

Part of the picture	L^*	a^*	b^*	h_{ab}^*	C_{ab}^*
Forehead of the Madonna	81 (±13)	4 (±2)	37 (±2)	84	37
Forehead of the angle	78 (±13)	13 (±3)	39 (±9)	72	41
Leg of St.John	71 (±2)	19 (±4)	46 (±5)	68	50
Robe of Mary	42 (±10)	-12 (±2)	21 (±7)	300	24

Table 2

Skin tones of the forehead of the Madonna, measured with the Photoshop eye-drop tool on artefacts from different databases reproducing the Virgin on the Rocks, National Gallery London version

L^*	a^*	b^*	h_{ab^*}	C_{ab}^*
96	-3	19	279	19
88	5	9	61	10
99	-5	22	283	23

Table 3

Average skin tones, colour of the robe of Maria and their standard deviations (in brackets) for four parts of the Madonna of the Rocks (Louvre) painting: (A), and of the Virgin of the Rocks (Nat. Gal., London) painting: (B); using the i1 instrument, based on seven Internet reproductions

Part of the picture	L^*	a^*	b^*	h_{ab}^*	C_{ab}^*
A.) Forehead of the Madonna	82 (±11)	12 (±4)	39 (±6)	73	41
Forehead of the angle	80 (±11)	21(±6)	45 (±11)	75	50
Leg of St.John	67 (±11)	18 (±5)	36 (±10)	63	40
Robe of Mary	48 (±7)	0 (±3)	2 (±4)	-	2
B.) Forehead of the Madonna	88 (±13)	7 (±6)	23 (+14)	73	24
Forehead of the angle	90 (±4)	6 (±5)	25 (±17)	77	26
Leg of St.John	87 (±5)	9 (±4)	27(±10)	72	28
Robe of Mary	55(±2)	3 (±4)	-17 (±5)	280	17

Table 4

Average skin tones, colour of the robe of for four parts of the Madonna of the Rocks (Louvre) painting: (A), and of the Virgin of the Rocks (Nat. Gal., London) painting: (B); using the i1 instrument, based on a printed book image

Part of the picture	L^*	a^*	b^*	h_{ab}^*	C_{ab}^*
A.) Forehead of the Madonna	77	3	35	85	35
Forehead of the angle	72	10	40	76	41
Leg of St.John	72	12	34	71	36
B.) Forehead of the Madonna	74	13	22	59	26
Robe of Mary	45	-1	-9	264	9

Similar investigations were made using the famous picture Mona Lisa, taken from [13] and [14], and the Lady with an Ermine, taken from [14] and [16]. In these artefacts, the colour of the forehead was investigated. We show the average results obtained when the measurements were taken on the monitor screen by Photoshop and by i1, as well as from albums, using the i1 instrument.

Table 5
Average skin tones and their standard deviations measured on the forehead of the Mona Lisa and the Lady with an Ermine

Picture and measurement	L^*	a^*	b^*	h_{ab}^*	C_{ab}^*
A.) Mona Lisa, Photoshop	84 (±5)	5 (±5)	53 (±11)	85	53
Mona Lisa, monitor, i1	87 (±3)	9 (±2)	49 (±11)	80	50
Mona Lisa, album, i1	63 (±3)	9 (±2)	30 (±2)	73	31
B.) Lady w. Er., Photoshop	80	14	38	70	40
Lady w. Er., monitor, i1	78	20	41	64	46
Lady w. Er., album, i1	73	7	24	74	25

2.1 Paintings by Vincent van Gogh

As another example, we selected another masterpiece, Vincent van Gogh's Bedroom, available as three original paintings now in the Art Institute of Chicago, the van Gogh Museum, Amsterdam and the Musée d'Orsay. The big difference compared to Leonardo's paintings is that, while the originals of the two Madonna/Virgin on the Rocks paintings are very similar and radiate the same feeling, the three van Gogh paintings show exactly the same room but painted in very different moods; thus the differences in coloration must be reproduced exactly in order to be able to evaluate the differences. Three Internet databases [19]-[21] (in one of them, several versions of the painting were found) and two books [22], [23] and an art poster [24] have been included in this search.

Again, both the Photoshop eye-drop technique and the i1 instrument were used for the picture displayed on the monitor, and the i1 was used for measuring colours in the printed versions. Figure 3 shows a black-and-white reproduction of one of the pictures, in which the five areas where measurements were taken are shown by white circles. The graphical part of the three originals is very similar and one has to look at the details of the paintings carefully to see the differences; on the other hand the coloration of the three originals is strikingly different.

Number 1 is a part of the bluish green window, 2 represents a part of the blue wall, 3 is a part of the yellow pillow, 4 is a reddish eiderdown, 5 is a brown wood colour. Table 6 shows in the example of the van Gogh Museum Amsterdam version the colorimetric values measured on three artefacts downloaded from the Internet, measured with the i1 instrument.

Figure 3
Vincent van Gogh's The bedroom painting, The Art Institute of Chicago version

Table 6
Colorimetric data for D50 illumination and 2°observation of artefacts downloaded from three Internet databases of Vincent van Gogh's Bedroom, van Gogh Museum Amsterdam version, measured with i1 instrument

1.) window	L^*	a^*	b^*	h_{ab}^*	C_{ab}^*
Database 1	59	-12	28	293	30
Database 2	66	-5	41	277	41
Database 3	77	-13	47	285	49
Average (AVE)	*67*	*-10*	*39*	284	40
Standard deviation (STD)	*9*	*4*	*10*		
2.) wall					
Database 1	58	-14	-6	203	15
Database 2	79	-7	-22	252	23
Database 3	86	-6	-12	243	13
Average (AVE)	*74*	*-9*	*-13*	235	16
Standard deviation (STD)	*14*	*5*	*8*		
3.) pillow					
Database 1	87	1	53	89	53
Database 2	87	11	52	78	53
Database 3	85	-1	51	271	51
Average (AVE)	*86*	*4*	*52*	86	52
Standard deviation (STD)	*1*	*7*	*1*		

4.) eiderdown					
Database 1	44	47	23	26	52
Database 2	49	55	31	29	63
Database 3	39	37	16	23	40
Average (AVE)	*44*	*46*	*23*	27	51
Standard deviation (STD)	*5*	*9*	*7*		
5.) bed, wood					
Database 1	70	42	54	52	68
Database 2	64	44	50	49	67
Database 3	77	20	62	72	65
Average (AVE)	*70*	*35*	*55*	58	65
Standard deviation (STD)	*7*	*13*	*6*		

As a next step, the results via the three measurement techniques (Monitor picture with Photoshop and i1, printed copy with i1) were compared. All three Internet versions and a book copy were measured. The average measurement results are seen for the Amsterdam version of "The bedroom" in Table 7.

Table 7
Colorimetric for D50 illumination and 2°observation determined on artefacts of Vincent van Gogh's Bedroom, van Gogh Museum Amsterdam version

1.) window:	L^*	a^*	b^*	h_{ab}^*	C_{ab}^*
Internet picture, Photoshop eye-drop	68	-15	47	288	49
Internet picture, i1 instrument	67	-10	39	284	40
Printed copy, i1 instrument	81	-6	49	277	49
AVE	72	-10	45	283	46
STD	8	5	6		
2.) wall					
Internet picture, Photoshop eye-drop	71	-12	-11	223	16
Internet picture, i1 instrument	74	-9	-13	235	16
Printed copy, i1 instrument	72	-11	-10	222	15
AVE	73	-11	-11	225	16
STD	2	2	2		
3.) pillow					
Internet picture, Photoshop eye-drop	83	2	64	88	64
Internet picture, i1 instrument	86	4	52	86	52
Printed copy, i1 instrument	65	9	40	77	41
AVE	78	5	52	85	52
STD	12	4	12		

4.) eiderdown					
Internet picture, Photoshop eye-drop	37	52	47	42	70
Internet picture, i1 instrument	44	46	23	27	51
Printed copy, i1 instrument	55	23	33	55	40
AVE	45	40	35	41	53
STD	9	15	12		
5.) bed, wood					
Internet picture, Photoshop eye-drop	69	34	70	64	78
Internet picture, i1 instrument	70	35	55	58	65
Printed copy, i1 instrument	70	12	54	77	55
AVE	70	27	60	66	66
STD	1	13	9		

Similar measurements were made on three Internet versions of the image from the Artistic Institute, Chicago, and on two Internet copies of the d'Orsay version of the "The Bedroom" picture.

3 Discussion

As can be seen from the different tables, the colours of the selected objects show considerable scatter. Investigating Leonardo's paintings, if a more detailed analysis is made, some quite unexpected discrepancies can be found: e.g. one of the databases contained four artefacts of the Madonna of the Rocks. In three of them the L^* value (lightness) of the complexion of the Madonna was within 1.5%, but the fourth one differed by almost 30%. Similar differences were found also for the lightness of other parts of the picture, but the hue angles of the objects were quite close to each other.

The Mona Lisa complexion lightness was quite similar in the three Internet databases, but the book reproduction differed considerably, however. On the other hand the hue angle differences were within acceptable tolerances.

Analysing the data of the van Gogh paintings, one must state that the artefacts of the same original differ considerably and not systematically in the different databases. This can be seen for example on the data as reproduced in Table 6: Comparing the CIE lightness data of the three datasets, we see e.g. that while for the pillow, the first two show the same value ($L^* = 87$), and the third one is only slightly lower ($L^* = 85$), for the bed colour the CIE lightness as shown in the third database is 10% higher than that from database number 1. This brings already an imbalance in the coloration of the artefact. Also, the hue angles show considerable differences, especially for the bed colour: In one case we see an almost orange colour, while in the other case it is a pale yellowish hue.

Similar differences can be found also for the blue wall colour, although in that case the lightness of the wall is much higher in the artefact of database 2, compared to database 1, which is just the opposite as for the bed colour. In summary, we must state that the three colorations used in the three databases deliver quite different messages to the viewer. And this is not a simple coding error of the originally taken analogue data, as in that case we would see systematic distortions, less obvious to the human eye.

4 Consequences

We agree with Borbely [27] that to reproduce colored images correctly, colour management has to be used and even in that case with modern LCD displays problems with crosstalk in the display might produce further problems. Thus when taking the digital images, all the background information should be captured; and similarly, the reproducing projector must to be calibrated. The remaining small errors produced by differences between the monitor and the projector can usually be neglected.

4.1 Consequences for the Art Teacher

As shown in the discussion section one observes quite often in different artefacts of one and the same original image that the colours of different objects move in different directions of colour space.

As regards the Madonna/Virgin on the Rocks, it is interesting that if one compares not two extreme artefacts, one finds that Leonardo used decades later practically the same colours: looking at Tables 3 and 4, if one considers the scatter between the different artefacts, it is striking how similar the lightness and the hue angles of the forehead of the Madonna in the two paintings are. (As mentioned, for the Louvre version in one and the same database two artefacts were found that showed strikingly different coloration; such "bad" reproductions should not be considered.) It is interesting that the chroma (the vividness of the colour) is different in the artefacts of the two paintings (see C_{ab}* for the forehead both of the Madonna and of the angle, but also of the leg of St.John, i.e. "skin tones"): on the London version these flesh tone colours are less vivid, but the lightness is practically the same. From this, one can conclude that these artefacts reproduce correctly the three dimensions of the flesh tones (hue, lightness and chroma). Leonardo seems to have used similar colour attributes also for his other (analysed) paintings, as is shown in Table 5 for the skin tones of the Mona Lisa and the Lady with the Ermine.

The picture is not so clear in the case of the van Gogh paintings. There are on the one side large differences for one and the same object of the same painting

if the artefact is take from different databases, but because the human eye is more sensitive to them, it is more critical if the chromaticity of two objects changes in different directions in colour space. Thus, for example, as seen from Table 6, comparing Databases 1, 2 and 3, the window and wall lightness increase from 1 to 2 to 3, but the pillow lightness stays practically constant, and that of the eiderdown decreases. But what is even more critical is that, at the same time, the hue of the window changes from bluish towards greenish (decreasing hue angle), but for the wall colour the hue angle increases, from greenish towards bluish; thus, the hue difference between wall and window hue decreases. This can produce an imbalance in the picture's colour impression. Similar distortions can be observed when the colours of the van Gogh Museum artefacts are compared.

Such problems make it difficult for the art teacher to select the best reproduction setting for his equipment. All the fine tuning possibilities of present day image manipulating software (e.g. setting chromatic adaptation, gamma correction based on surround brightness, etc.) [6], based on CIECAM02 colour appearance model [28], [29], are in vain if the image providers do not supply the necessary metadata with the images.

4.2 Consequences for Technicians of Museums

Modern imaging technologies provide the means to tag the images with metadata describing all the information needed to reproduce the image in a colour correct form: information on the illumination used (not only correlated colour temperature, but spectral distribution, or at least colour rendering indices), spectral responsivity of the image-taking camera, its gamma characteristics, etc. These are all known when the picture is taken, and if it could be communicated together with the image, it would be possible to reproduce the image colour correctly, just as is done in many technical colour communication applications in the textile or paper industry.

Summary and Conclusion

Based on the examples discussed in this paper, we must conclude that the digital artefacts of famous paintings now available on the Internet are – at least partly – poor reproductions of the original. Techniques now available to set the colorimetric characteristics of the different imaging devices (monitors, printers, projectors) provide better agreement between these devices as to what one can expect by downloading artefacts from different databases. This is certainly a bad message for the art teacher who would like to use these images in his classes.

The first and most important message to the art teacher is not to rely on one single reproduction, downloaded from one database, but to check for more copies of the same painting, and to compare their colours before selecting one

to be shown in the classroom. On the other side, we should mention that on the receiving side, i.e. reproducing the pictures in the class-room, for the time being not much can be done to increase colour fidelity.

To the providers of the artefacts one should direct the plea to provide with the reproduction also some information as to how the reproduction was made: illuminant used to take the picture, encoding, eventual transformations (e.g. lightness scale distortions), etc. This could help in the future to set the necessary transformations to get on the screen the colour impression one would have by looking at the original in the museum.

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Measuring Railway Market Attractiveness: Evidence from Visegrád Countries

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Abstract: This paper analyses the liberalization procedure of the passenger and freight railway transport market in the Visegrád states. The paper applies macro and micro environment analysis to demonstrate the situation of these post-communist countries and introduces the regulatory impact on the railway market supply while concentrating on intra-modal competition. The aim of the paper is to highlight how railway liberalization has changed the shrinking railway market in order to define a strategic policy intervention, with the express purpose of increasing the competitiveness of railway transport and solving efficiency problems. The paper introduces the rate of railway market attractiveness (RAMATE rate) in order to compare the attractiveness of the different railway markets of the European Union for new entrants and the degree of deregulation.

Keywords: railways; market liberalization; market attractiveness; Visegrád States; European Union

1 Introduction

Upon consideration of their common historical past[1] and their geographical and economic comparability, the Czech Republic, the Slovak Republic, Poland and Hungary established the Visegrád Group[2] in 1991. These post-communist countries made the transition from planned to market economies, which resulted in remarkable economic and social development. However, such progress was not made within the railway industry. Prior to the introduction of the First Railway Package, even EU legislation could not achieve significant results. Since that First Package, however, the railway companies have been reformed; vertical and horizontal separations have begun, and so business activities have been separated

[1] The historical antecedent of the league was the summit of the Hungarian (Charles Robert), the Czech (Luxembourgish John) and the Polish King (III. Calvin) in 1335. The rulers came to an understanding about political and commercial affairs in the then seat of the Hungarian King, the Visegrád Royal Palace.

[2] The alliance was originally entitled the V3, after the dissolution of Czechoslovakia, the group became the Visegrád Four or V4.

or outsourced. The transition of the railway market, (the reorganization, the open access to infrastructure, the freight and the international passenger transport liberalization), has intensified competition, primarily in the freight market, although the former operators still prevail in this segment. In the V4 domestic passenger railway market, there are only a few new operators, the majority of which are in Poland. Intra-modal competition has been boosted with the permission of cabotage.

Despite these results, as of 2010 the full implementation of the First Package had not been realized in 22 EU states, including the Visegrád Four. There have been failures with the regulatory board, which has not been set up in every country, and/or, is not independent. The main problem is that the infrastructure management companies and their charging functions are dependent upon the owners of the incumbent railway companies. However, the access charge to infrastructure should be the basis of competition and open markets.

Considering the above circumstances as a starting point, in this paper I compare the main indicators of the V4 member countries and summarize the present situation of railway transport in light of liberalization. The paper introduces the rate of railway market attractiveness (the RAMATE rate) in order to compare the attractiveness of the different markets for new entrants and the degree of deregulation. In this spirit, the paper points out the discrepancies of the process and draws conclusions on railway transport planning for policy-makers and infrastructure managers. The scope of my paper is to support the decision of allowing operators to enter into the market.

2 Regulation Framework and a Review of the Literature

Railway transport liberalization started with Directive 91/440/EEC, which required that railway companies separate railway infrastructure from transport services. This was to be achieved initially by accountancy to ensure non-discriminative usage, and by the charging of rail track for EU member states. Thus it allowed new entries into the rail market and therefore induced competition. The aim of the directive was to increase operational efficiency and transparency, in the first instance, especially in the case of subsidies. However, it has not been applied extensively and has had significant results only in the United Kingdom and Germany. While the spread of the directive occurred in these countries, the subsidies of railway services were cut in the V4 and a few non-core business activities were outsourced (see detailed discussion in [20]).

2001/12-13-14/EC was introduced to achieve the overall liberalization targets. These directives are also known as the First Railway Package, which allows

operation through an independent infrastructure management company in the EU network to enhance competition. As a part of the Second Railway Package, Directive 2004/51/EC is valid throughout the whole European network and the liberalization of the freight transport was planned to come into force by 2007. As Eisenkopf and his co-authors [7] point out, the directives are the legal framework of liberalization; but in fact, open markets and intra-modal competition can be achieved only in the long-term.

Monami [33] has identified seven key dimensions (7Ds) of passenger transport liberalization, which enable comparison of the countries with qualitative market features. The 7Ds contain the dependence of the regulatory body, vertical and horizontal integration, the duration of the contracts and the resulting obligations for all market players, the production and revenue risk-sharing among them, the opportunities of the management within the contract and the allocation of subsidies. To determine and compare the degree of passenger and freight railway market opening, Kirchner in cooperation with IBM has developed the more detailed Rail Liberalization Index (LIB Index) in a similar spirit, although it is more market-oriented and does not deal with the allocation of subsidies [24], [25]. The LIB Index contains the LEX and ACCESS sub-indices. The former indicates the legal access barriers to the railway market in the given country; the latter defines the accessible market in particular for external railway undertakings. The COM Index measures the competitive dynamics of railway market share change. These indicators show market liberalization from the point of view of the entering railway undertakings in EU countries together with Norway and Switzerland. These measures apply subjective elements. As compared with LIB and COM indices I would like to introduce a more exact, data-based rate.

Wetzel [45] points out the regulatory reforms and the environmental effects on technical efficiency from 1994 to 2005. According to Wetzel, a high share of electrified lines, freight oriented railways on a less dense network and an independent regulatory body have positive effects on technical efficiency. Also to Wetzel's mind, it is arguable that her results show that access rights for passenger services have negative effects on efficiency.

However, Ludvigsen and Osland [31] observe that although railway freight transport has a lot of private entrants, there is a lack of inter-modal competition, primarily because of service quality, which cannot compete with road operators. They find that neither the state-owned national monopolies nor the market are efficient. This inefficiency induces that the road freight transport has remained dominant, despite the fact that it shows more negative externalities. According to their study, intra-modal competition exists within the Visegrád countries only in Poland and in the Czech Republic. Szekely [38] and Hilmola [37] have studied Hungary and Poland and confirmed that the incumbent railway operator of Hungary prevails, albeit in a serious financial crisis. However, the incumbant operator of Poland has already had remarkable results, although the authors have disputed that deregulation and privatization have intensified competition. Since

the appearance of these papers, I have found that intra-modal competition has been intensifying principally in Poland and in the Czech Republic, and although with smaller magnitude, also in Hungary. This is due in great part to the introduction of the Third Railway Package, which outperformed the previous ones. Owing to this, market reforms have taken place overall and international passenger transport has been liberalized since 2010 as the main principle. However, despite these developments, the Third Railway Package has not raised the railway market share, which was originally the main aim of the reforms.

Lang and his co-authors [29] emphasize, while conducting a game-theoric model of a fully vertically separated, liberalized railway market, that more competitors reduce prices per kilometer, thus improving the performance in terms of train kilometers and social welfare. Mainly ticket revenues based on competitive tendering should be the method of entry, which should fall within regional authorities' cognizance, as suggested by Link [30], while focusing on the regional traffic of railway passenger transport. Alexandersson [1] agrees with competitive tendering, because it can create a competitive environment and develop the market, and thus improve the efficiency of the companies and in turn the services. For the state, it also leads to lower subsidies and a reduction in the need to control services which should be henceforth within the domain of the public sector. Assessing the railway freight liberalization in Poland and Germany, Laisi [28] has confirmed that vertical integration in Poland, and start-up in Sweden, like in other Western European countries, have been the most commonly used entry strategies. The entry strategies, in connection with cultural differences between Eastern and Western Europe are studied by Vágási [43].

Investigating the competition on the freight market, Božičnik [3] points out that liberalization allows financially well-founded, incumbent operators to expand their activities for the European Network. Financially weak ones and small railway undertakings should specialize in market segments, especially niches, or in extreme cases, they could be abolished.

The basis of competition is infrastructure charging, which should be proportional and non-discriminative within the EU. Charge should be internalized externalities and based on marginal social cost; it should vary through different types of trains, time and space, and it should be proportional to usage. There are numerous studies (e.g., [5], [32], [36]) on how to implement the new pricing method, or rather, on how to amend it in practice. This new pricing system should be introduced gradually, at the same time as all transport modes, except in railway transport, which should be postponed for sustainability reasons. The members of the Visegrád Four, with the exception of Hungary, apply higher infrastructure charges for freight transport than they do for passenger services. These higher charges can decrease the competitiveness of rail transportation compared to other modes.

Deregulation of the Eastern European railways is studied by Tánczos and Bessenyei [39], who highlight the lack of national transport strategies. Žižka [46]

compares these Central-European countries to New Zealand, which used to be characterized by low productivity and operational efficiency in its pre-liberalization period as well, and indicates that privatization can increase economic effectiveness considerably. The criteria of the Swedish, German and French models of liberalization are identified by Nash [34] and adopted in this paper.

The previous literature has exhibited liberalization without highlighting the institutional background of the railway reform. My paper introduces the regulatory impacts on the railway market supply while concentrating on intra-modal competition. The scope of my paper is to present a more detailed, country-specific analysis of the reform and the transition of the railway market, focusing within the Central European Region.

3 Methodology and Data Sources

On the one hand, this paper is structured in a deductive way, which is, based on the review of the relevant literature and existing models. On the other hand, I also use some inductive elements, for example, in the frame of data-based, country analysis. In the course of my essentially ex-post observation, I conduct the indicators which can characterize liberalization and the attractiveness of the railway markets. My hypothesis can be formulated as: 'The V4 railway market liberalization has occurred and consequently intra-modal competition has been intensifying; therefore, the V4 markets are attractive for entrants.'

The LIB Index and COM Index of IBM [24], [25] are based on quantitative research, and yet, nevertheless, these indicators apply subjective elements (e.g. "Process duration for obtaining information"). On account of the introduction of EU directives, there are determinants which can almost be constant because little impact has been assigned to them, such as the degree of vertical separation of the incumbent companies, although there are some exceptions to this rule (e.g. Poland). However, it would be useful to take into account the "Status of independence of the incumbent from state", but there are unfortunately no objective statistics about this. The main difference between IBM's index and the RAMATE rate is that the LIB and COM indices approach the problem from the railway undertakings point of view, while the RAMATE rate, on the other hand, approaches it in terms of the railway market supply and demand. On the other hand, the supply side constitutes the railway undertakings and their performance belongs to the demand side. One further difference between the RAMATE rate and the IBM Indices is that the RAMATE rate introduces charges of the operations as a new variable, which can be a leading argument in market entry decisions.

Nevertheless, the RAMATE rate uses infrastructure charges as a variable from the ACCESS Index and it also applies the modal split development from the COM Index to present market facilities. To demonstrate how the given market is saturated, the number and market share of external railway undertakings are translated from the COM Index too. However, the RAMATE rate treats the legal background as well as the consequent entry barriers as a constant, although the EU directives have been adopted differently in the member states. The legal interdependence is the limitation of the RAMATE rate, which is taken into consideration in the case studies of the V4.

According to the relevant literature, the variables of the passenger and freight railway market attractiveness were identified (see Tables 2, 3). These determinants are categorized into two groups: the first one defines the infrastructure and its charges, and in doing so, defines the accessibility of the market. The relevant market is characterized by the performance of the railway undertakings and appoints the availability for both the licensed operators and the new entrants. On the grounds of accessibility and availability, Rail Market Attractiveness can be derived by averaging the main ratios: accessibility and availability.

The variables of passenger and freight market accessibility vary in the description of the railway market and the infrastructure access charges from each other. The share of double or more track lines can depend not only on development, but also on geography, despite the fact that this share sets the conditions of the transport.

The main aim of this paper is to provide the most recent detailed picture of the emerging liberalized railway market on the basis of the RAMATE rate. That is why the latest available data are used. For example, the data in the case of valid licenses and freight transport charges refers to 2011.

The research is based on international secondary research and on internet databases of statistical offices and railway organizations, such as the CER (Community of European Railway and Infrastructure Companies), the ERADIS (European Railway Agency Database of Interoperability and Safety), the Eurostat, the IBM, the ITF (International Transport Forum), the KSH (Hungarian Central Statistical Office), the UIC (International Union of Railways) and the Rail Market Monitoring Scheme (RMMS), which has been set up by the European Commission.

UIC provides statistics on the main indicators of the countries and also on the operators, which can be used for calculations, such as the network density and the length of the lines relative to the population. The givens of the network can be described with the share of electrified lines and the amount of double or more track lines. To give a reliable picture of the operators' performances, Eurostat statistics are used. These combined with the length of the lines ensure that the intensity of network use can be reckoned. The modal split of railway transport shows the importance of the railway sector in the given country. The change of modal split can foreshadow the potential market too. The GDP per capita in

Purchasing Parity Standard can be obtained also from the Eurostat database, which is appropriate for the comparison of the welfare of the inhabitants.

The infrastructure access charges are given in the network statements of the infrastructure managers, which are aggregated by ITF. These charges are based on different calculation methods. The limitation of the model is that it is unable to take into account additional costs, discounts and penalties (e.g. to achieve punctuality) related to infrastructure, which can arise in different amounts from negligible to significant, as with the application fee of 750 euro in Ireland [21]. The average infrastructure charges are calculated for Intercity and separately for freight trains (960-3000 ton).

Data relating to the operating licenses are available at ERADIS via an online request, except in some cases, such as with the Polish passenger and freight railway undertakings, which should be extracted from the national databases such as the UTK (Urząd Transportu Kolejowego/ Rail Transport Agency) in Polish or from the RMMS report of the European Commission [8] [9] [42]. Although the number of operating railway undertakings is not the same as the number of valid operating licenses, it does show how attractive the legal and the market environment is. Within the framework of the RMMS, the market share of the non-incumbent railway undertakings referring to 2007 and 2009 was studied [9]. The lack of recent statistics indicated that in the case of freight transport, the data of non-incumbent market shares in Slovakia and Sweden refers to 2007 only. In the case of passenger transport in Austria, Italy, Romania and Germany, there are also only data from 2007 available.

The inland passenger transport fares can be found in the on-line timetables of the railway companies, in some cases in their tariff tables, or on request by e-mail. An average passenger route of 50-55 km is considered, because the average passenger transport distance of the EU is 52,4 km, which means, in addition, that the V4 has almost the same, with 53,1 km in 2009 [17]. These tariffs are suitable for comparing the different price levels of the countries, although the diverse discounts are not considered. The tariffs can be different for the same distance in some countries; alternatively, in other countries different criteria are used: for example, the bases of the fares in Denmark are the zones, and in Luxembourg the time of the journey. There are also differences in service quality, such as principally the duration, which can be 30-60 minutes (process), the condition of the trains and the stations (physical evidence) and the crew including the conductor (personnel) during the journey.

The international charges of freight transport are published on the websites of the operators without any discounts or are available on request via e-mail. In the case of Finland, Ireland, Spain, Portugal and the United Kingdom, the charges are based on expert estimates of a forwarder [6], [35]. As an average freight transport, 200 km distance and 25 ton goods are applied, because the average freight rail distance is 227,8 km in the EU and 187,4 km in the V4 countries in 2009 [15].

Although the charges are dependent on a number of factors – the commodity being moved, the volumes and the specific origins, and the destinations – the aim of the paper is only to compare the price levels of the countries, and thus these features are not considered.

In order to collate the RAMATE rate in the EU countries, all of the values are related to the EU averages. The charges are reciprocated, because in terms of the index, the lower values are better, and so they get higher percentages in the rate.

The limitation of the model can be formulated as its sensitivity to outliers. To decrease this effect, the market volume of non-incumbent operators is reckoned as the valid licenses reduced by the incumbent company, multiplied by the market share of non-incumbent operators and divided by 100.

4 Similarities and Dissimilarities of the Main Feature of the Visegrád Four

The aim of the V4 community is to strengthen their previously shared interests in security and defense policies, to hold expert meetings on crisis situations and on economic, environmental, infrastructural, social and cultural issues, and also on public relations. The Visegrád Group cooperates within the EU and forms partnerships primarily with neighboring countries, the EU and NATO [44].

A similar background requires similar tasks and steps from the Visegrád Four, but the main characteristics, which may exhibit differences, should be taken into consideration. We can compare the main indicators of the V4 states in Table 1.

Table 1

The Main Indicators of the V4 [11, 16, 27]

Indicator	Territory	Population	Population density	GDP per capita in PPS	Length of lines	Density of lines
Unit	1000 km^2	million inhabitant	inhabitants per km^2	EU 27=100%	km	km/ 1000 km^2
EU 27	4 318,2	501,1[e]	116[e]	100	214 945	49,8
Czech Republic	78,9	10,5	133,8	82	9 477	120,11
Hungary	93	10	108,1	65	7 892	84,86
Poland	312,7	38,2	122	61	19 764	63,15
Slovak Republic	49	5,4	110,1	73	3 623	73,93

Notes: [e]Estimated value. Data refer to 2009.

Following the breakdown of the communist regimes which governed these states, these countries have been making thorough efforts to link their economies to the developed world. Market reforms have taken place, which exert significant impact on the integration into the global economy [19]. As a result of the transition process, all the V4 states joined the EU in 2004.

These Central European countries are export and industry-oriented. The average growth rate of these economies exceeds the European average. If we consider the GDP per capita based on PPS (Purchasing Power Standards) as the welfare indicator, the Czech Republic is the richest country among the V4, but its value is still below the EU 27 average.

Economic problems in the region have been significant (although Poland, which has a considerable internal market, has suffered the least). Exports and industrial production have plunged sharply; thus unemployment has risen. The Slovak Republic had already achieved the convergence criterions before the recession; therefore, it had the possibility to join the EMU at the beginning of 2009. As a member of the Euro zone, the Slovak Republic has not been directly concerned with the currency movements but a few industries have lost their competitiveness in comparison to the other V4 countries whose rates have weakened (see more detailed [26]). While the V4 countries who manage their own monetary policy could raise their exports, the Slovak Republic could not; thus it has also suffered from the crisis.

After the EU accession, the EU handled the Newly Associated States (NAS) as an entity within the scope of the New Neighborhood Policy, but the EMU enlargement with the Slovak Republic shows that the EU treats the NAS uniquely.

Poland has the largest territory and a considerable internal market requiring more mobility and transportation. Because of that, and its geographical location, transit traffic is not as significant as in the other V4 states. The Czech Republic has the most decentralized, extended railway network with the highest density in the European Union. Poland has the lowest level of line density among the Visegrád states, but it is still above the European average. The only country in the Visegrád states which has an above EU-27 average proportion of electrified and double track lines is Poland.

In these countries, modernization of infrastructure meant that public road transport increased quickly, but the improvement of the railway network fell behind. The main problems are the bad condition of the rail tracks and the related properties, as well as the rolling stock, which altogether induce low service quality. The emerging financial difficulties, due to the severe recession, are further obstacles to the modernization of the industry in the V4 countries.

These problems persist, despite the fact that the aim of the development of railway transport is not only to meet EU regulation purposes, but also to increase competitiveness and efficiency, taking sustainability into account.

4.1 Different Reform Paths of the Visegrád Four

The V4 countries have a history of railway transport that dates back more than 160 years. The development of their industries has also been quite similar. It is still characterized by a fixed, high and dry structure and management. After the

transition of the political regimes, sweeping changes occurred in the economy, but not in the railway industry. The EU accession processes as well as harmonization represent a great leap forward, but the breakthrough has happened due to open access to the railway infrastructure.

On the basis of the Directives, institutional frameworks have been developed and reorganizations have been taking place at the railway companies. The vertically integrated sector had to be divided into business units. Foremost in this, the infrastructure management was separated from operations between 2003-2004 (SŽDC, ŽSR, VPE, PKP PLK). The capacity management companies are actually making profits, excluding ŽSR [4].

The incumbent passenger railway companies have remained state-owned. In the Czech Republic and in Poland the local governments are responsible for regional lines. Arriva-PCC was the first new rail market entrant into the passenger transport market in the V4; it has been transporting around three million people per annum in northern Poland since 2007. The short term goal of Arriva-PCC is to expand further in Poland and in the Czech Republic.

The freight companies (PKP Cargo, ŽSSK Cargo, ČD Cargo, Rail Cargo Hungaria) have started to function independently from the former incumbent companies since 2001-2007. In the V4 countries it can be observed that governments have been seeking to privatize mainly the non-core business activities and, in some cases, the freight operator. The investors are primarily other railway companies, albeit operators that not only have an interest in the market and the necessary experience, but also have access to considerable finances.

The reforms have taken place differently in each country. Nash has identified different reform models [34]. The Slovak Republic followed the Swedish model, which means that the infrastructure manager and also the major railway operator remain state-owned and, in this way, remain subsidized. Nevertheless, all of the responsibilities are separated. Poland has remained vertically integrated and manages its activity within a holding company, akin to the German model. The Czech Republic and Hungary have adopted the French model, and so a separate company is responsible for infrastructure management and charging. These seem to be independent; however, they are bound up with the major incumbent transport company, and so both remain monopolies in the public sector. The problem of this organizational integration whilst remaining dependent upon the state can be formulated in the question: How can free competition be ensured if the major company is favored? Nevertheless, the reforms can allow transparency; that is, it may help in reducing costs. In addition, infrastructure charging ensures competition and the revenue can be used for development.

To increase operational efficiency, several branch lines have been closed in Hungary, the Slovak Republic and in Poland, where for example almost 10,000 km of branch lines have been gradually closed over the past two decades. On average, four percent of railway employees were discharged annually from 1996

to 2009 in the V4 states. As a result, the pay-roll has been cut by more than 40% since 1996 [13], but the number of employees is still above the European Union average in all the examined countries.

As a consequence of these arrangements, the industry has been boosted by the limitation of monopolies and by the permission of intra-modal competition, and in this way by fostering the appearance of new rail market entrants, principally in freight transport.

4.2 The Railway Market Performances of the V4

In all the Visegrád states, mobility has been growing along with the passenger transport market. The railway market share has been decreasing almost in every country for more than 30 years and further decline is round the corner, because the motorization rate of the EU is showing a growing tendency. On the one hand, there is a quantitative reason: the increasing rate of car ownership. On the other hand, there is a qualitative one: the technological development related to travel circumstances, such as the level of service and the flexibility of travel in one mode in comparison to other transport modes.

The railway passenger modal split is the highest (12.3%) in Hungary among the V4 [12]. Although PKP has lost its market share significantly since deregulation, the volume of railway passenger transport has increased in the liberalized Poland (Figure 1). PKP is still one of the biggest railways; its performance was the fifth in the EU in 2009. ČD is the ninth, but it could not reach the EU average. [41]

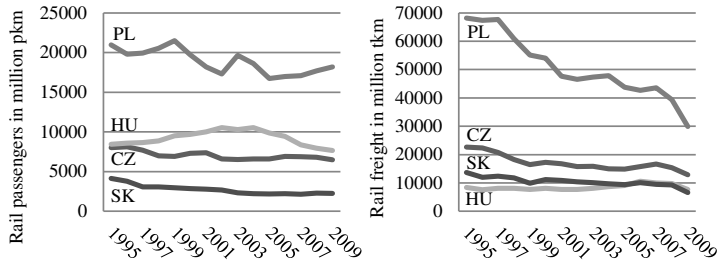

Figure 1

Rail passenger and freight transport in the states of Visegrád in 1995-2009 [22]

In the case of the railway freight modal split there has been a notable decrease, but railway transport still covers 20-24% of the freight market in the V4 countries [12]. Even though PKP Cargo has lost more than half of its market in the last fifteen years, it is still the second biggest cargo operator in the EU, while only DB AG exceeds its performance in 2009 [41].

5 Results

The passenger and freight RAMATE rates are calculated for the EU countries, which help to identify which are the most attractive railway markets and at what degree the liberalization of the Visegrád states is compared to the other EU countries.

According to the data for the EU countries, the railway network density determines the railway modal split and performance. The development of the railway infrastructure, such as the proportion of electrified and double or more track lines, is connected with the development of the country, and further, the railway performance, which is negatively correlated with tariffs. These effects, in part can be construed as due to price elasticity of demand, which is in parallel with Lang research [29], but contrary to that of Bekő [2].

If we analyze accessibility within the V4 (Tables 2, 3), we can draw the conclusion that the supply of the Czech infrastructure covers the country the most extensively, but Poland is better equipped with gauges and electricity, which, together with the lowest access charge for passenger trains, offers a favorable market for new operators. The low endowment of double or more track lines determines the poor position of Hungary, which also causes barriers in traffic flow and the accumulation of delays, and thus leads to customer dissatisfaction. The share of the main international corridors, the Trans-European Transport Network (TEN-T), is low in the Czech Republic, even though it is a transit country, as are the other Central European states.

The modal split of the passenger railway market (Table 2) is the highest in Hungary despite the fact that railway performance is decreasing and that transport fares have almost doubled in the last five years [14]. The most centralized passenger railway market is the Slovakian, although despite that, the performance and the modal split there are also low. The Polish market has created a competitive environment, so it is the most liberalized and attractive. Nevertheless, the fares within the Polish market exceed the EU average.

In the case of freight railway transport (Table 3), the market volume is outstanding in Poland even in comparison with the rest of the EU, which is linked to the size of the internal and external markets. In Hungary the very low infrastructure access charge can encourage market entry, and thus competition. Within the V4, only in the Czech Republic has the railway freight modal split increased in the last decade, which alludes to inter-modal competition and parallel opportunity for new entrants.

According to the results of the RAMATE rate, the hypothesis can be rejected for the freight railway market of Slovakia. The development of the other markets, including the passenger transport of Slovakia, can be attractive for entrants.

Table 2
Passenger Railway Market Attractiveness Rate [8], [9], [10], [11], [12], [16], [17], [18], [23], [40], [41], [42]

Attributes of the passenger railway market	UK	DK	DE	LU	SE	**PL**	NL	AT	**CZ**	BE	FI	**HU**	**SK**	FR	RO	ES	IT	LV	EL	BG	EE	SI	PT	LT	IE
Rail lines relative to population	48,1	70,8	75,2	102,0	196,6	**94,8**	32,0	126,7	**166,8**	60,9	203,4	**142,2**	**122,5**	99,0	91,7	60,1	51,7	152,5	41,5	99,8	126,8	110,6	48,9	96,5	78,9
Network density	118,4	87,9	167,8	188,1	40,1	**112,4**	137,2	122,6	**215,0**	208,6	31,1	**149,0**	**131,5**	108,9	80,4	52,9	100,1	51,9	34,4	66,5	36,5	107,6	54,9	48,1	48,5
Share of electrified lines	70,6	62,6	125,8	205,1	170,1	**129,5**	163,7	131,7	**63,9**	180,8	111,5	**77,0**	**93,7**	106,4	79,9	125,5	153,2	29,5	22,3	146,9	30,6	88,2	110,6	14,9	5,8
Share of double or more track lines	211,2	124,5	153,3	145,7	52,0	**124,7**	196,6	102,0	**56,8**	222,5	27,6	**43,3**	**80,2**	160,4	77,3	92,2	128,1	47,7	58,1	67,0	54,8	76,9	61,0	61,9	74,1
Share of TEN-T railway lines	111,0	79,6	77,4	143,7	87,8	**48,3**	120,8	87,5	**46,6**	111,5	110,4	**66,7**	**71,5**	76,5	56,5	126,1	104,2	129,9	163,5	104,2	135,9	87,2	119,9	107,2	125,6
Average access charge for Intercity passenger trains	95,0	853,9	50,9	99,8	290,5	**233,7**	139,0	88,8	**168,0**	49,7	295,1	**120,2**	**122,5**	76,8	89,0	213,9	77,4	57,8	345,5	67,0	132,3	118,5	156,8	48,8	59,9
Accessibilty of the passenger railway market	**109,0**	**213,2**	**108,4**	**147,4**	**139,5**	**123,9**	**131,6**	**109,9**	**119,5**	**139,0**	**129,8**	**99,7**	**103,6**	**104,7**	**79,1**	**111,8**	**102,4**	**78,2**	**110,9**	**91,9**	**86,2**	**98,2**	**92,0**	**62,9**	**65,5**
GDP per capita in PPS	112,0	121,0	116,0	271,0	119,0	**61,0**	131,0	124,0	**82,0**	116,0	113,0	**65,0**	**73,0**	108,0	46,0	103,0	104,0	52,0	94,0	44,0	64,0	88,0	80,0	55,0	127,0
Modal split of passenger rail transport	93,2	128,8	117,8	58,9	127,4	**84,9**	132,9	152,1	**97,3**	98,6	74,0	**168,5**	**89,0**	138,4	104,1	75,3	78,1	72,6	17,8	56,2	28,8	39,7	56,2	13,7	46,6
The change of passenger rail modal split among 1995-2008	181,0	136,1	128,9	133,7	162,6	**46,9**	108,4	145,4	**135,9**	42,1	117,1	**113,2**	**121,3**	63,5	33,6	121,6	15,6	96,9	157,8	77,0	34,6	60,4	67,6	121,1	77,6
Passenger rail performance per capita	131,4	171,4	151,0	107,2	182,5	**72,9**	151,8	186,9	**94,8**	149,6	116,7	**122,3**	**64,1**	217,5	43,7	77,1	126,5	50,7	22,6	43,1	28,5	58,3	60,8	10,6	58,0
Market volumen of non-incumbent passenger operators	1078,9	117,7	745,4	0,0	128,7	**351,9**	5,4	35,3	**0,1**	0,0	0,0	**1,8**	**4,6**	0,0	1,3	0,0	2,9	11,3	0,0	0,5	14,1	0,0	0,0	0,0	0,0
Inland full price, second class, single ticket fares for 50-55 km	52,2	50,4	54,0	428,8	66,6	**82,5**	72,3	58,5	**216,6**	86,9	126,1	**189,7**	**255,2**	69,9	428,8	67,3	162,8	338,5	119,1	293,7	296,4	134,0	142,9	219,5	41,5
Availability of the passenger railway market	**274,8**	**120,9**	**218,9**	**166,6**	**131,1**	**116,7**	**100,3**	**117,0**	**104,4**	**82,2**	**91,1**	**110,1**	**101,2**	**99,5**	**109,6**	**74,1**	**81,7**	**103,7**	**68,5**	**85,7**	**77,7**	**63,4**	**67,9**	**70,0**	**58,4**
Attractiveness of the passenger railway market	**191,9**	**167,1**	**163,6**	**157,0**	**135,3**	**120,3**	**115,9**	**113,5**	**112,0**	**110,6**	**110,5**	**104,9**	**102,4**	**102,1**	**94,4**	**92,9**	**92,0**	**90,9**	**89,7**	**88,8**	**82,0**	**80,8**	**80,0**	**66,4**	**62,0**

Table 3

Freight Railway Market Attractiveness Rate [6], [8], [9], [10], [12], [15], [16], [23], [27], [35], [40], [42]

Attributes of the freight railway market	DE	SE	UK	LV	BE	LU	**PL**	EL	EE	AT	DK	NL	FR	**HU**	LT	IT	SI	**CZ**	RO	PT	ES	**SK**	BG	FI	IE
Network density	167,8	40,1	118,4	51,9	208,6	188,1	**112,4**	34,4	36,5	122,6	87,9	137,2	108,9	**149,0**	48,1	100,1	107,6	**215,0**	80,4	54,9	52,9	**131,5**	66,5	31,1	48,5
Share of electrified lines	125,8	170,1	70,6	29,5	180,8	205,1	**129,5**	22,3	30,6	131,7	62,6	163,7	106,4	**77,0**	14,9	153,2	88,2	**63,9**	79,9	110,6	125,5	**93,7**	146,9	111,5	5,8
Share of double or more track lines	153,3	52,0	211,2	47,7	222,5	145,7	**124,7**	58,1	54,8	102,0	124,5	196,6	160,4	**43,3**	61,9	128,1	76,9	**56,8**	77,3	61,0	92,2	**80,2**	67,0	27,6	74,1
Share of TEN-T railway lines	77,4	87,8	111,0	129,9	111,5	143,7	**48,3**	163,5	135,9	87,5	79,6	120,8	76,5	**66,7**	107,2	104,2	87,2	**46,6**	56,5	119,9	126,1	**71,5**	104,2	110,4	125,6
Average access charge for 960-3000 ton freight trains	158,0	586,0	67,5	63,6	253,2	167,2	**62,0**	643,1	44,0	107,2	426,5	106,7	213,8	**274,9**	36,9	173,6	220,5	**64,1**	106,5	276,8	200,0	**45,3**	52,2	94,5	111,5
Accessibilty of the freight railway market	**136,5**	**187,2**	**115,8**	**64,5**	**195,3**	**170,0**	**95,4**	**184,3**	**60,4**	**110,2**	**156,2**	**145,0**	**133,2**	**122,2**	**53,8**	**131,8**	**116,1**	**89,3**	**80,1**	**124,6**	**119,4**	**84,4**	**87,4**	**75,0**	**73,1**
Modal split of freight rail transport	106,2	190,5	67,1	354,7	76,7	11,7	**98,6**	11,2	267,8	185,0	46,7	24,9	80,8	**104,7**	203,8	45,7	81,3	**112,3**	98,6	29,0	17,3	**99,6**	60,5	122,5	3,0
The change of freight rail modal split among 1994-2009	54,5	123,4	233,6	22,5	35,9	247,3	**45,3**	101,7	100,2	149,1	138,9	115,6	157,8	**95,8**	78,9	86,1	54,6	**147,5**	50,6	95,9	118,1	**67,3**	61,8	8,3	109,1
Intensity of network use	132,9	108,6	61,2	464,3	83,3	34,0	**102,7**	14,4	299,2	143,6	37,3	90,3	44,5	**46,0**	314,4	49,0	107,2	**62,7**	48,1	35,8	23,4	**89,8**	35,4	70,1	1,9
Market volumen of non-incumbent freight operators	1047,0	121,4	333,4	8,8	7,6	0,0	**363,9**	0,0	91,2	25,6	11,3	69,1	12,0	**68,4**	0,0	17,7	1,9	**74,4**	204,1	0,7	8,0	**3,5**	29,9	0,0	0,0
International freight charges for 200 km, 25 ton	76,5	129,0	79,8	108,8	83,7	83,7	**121,1**	122,2	108,8	89,4	117,3	83,7	78,3	**99,4**	108,8	116,3	130,2	**91,5**	113,5	93,6	93,6	**115,8**	116,3	114,0	92,1
Availability of the freight railway market	**283,4**	**134,6**	**155,0**	**191,8**	**57,4**	**75,3**	**146,3**	**49,9**	**173,4**	**118,5**	**70,3**	**76,7**	**74,7**	**82,9**	**141,2**	**63,0**	**75,0**	**97,7**	**103,0**	**51,0**	**52,1**	**75,2**	**60,8**	**63,0**	**41,2**
Attractiveness of the freight railway market	**209,9**	**160,9**	**135,4**	**128,2**	**126,4**	**122,6**	**120,8**	**117,1**	**116,9**	**114,4**	**113,3**	**110,9**	**103,9**	**102,5**	**97,5**	**97,4**	**95,6**	**93,5**	**91,5**	**87,8**	**85,7**	**79,8**	**74,1**	**69,0**	**57,2**

Concluding Remarks – The Situation of the Visegrád Railways

The legal framework of liberalization was provided by the EU directives, but there have been different realization schemes. The convergence of these directions can be defined as the following: firstly, the establishment of regulatory bodies, which has occurred in the examined countries. Secondly, the actual functioning of these bodies, such as can be observed in congestion charging, which has discrepancies everywhere. From that point onwards, there are continuous efficiency problems and operators have had to contend with financial difficulties.

Policy makers should firstly ensure that infrastructure management companies are more independent, in order to then ensure real competition and discourage the dominance of incumbent operators. These remnants of former communist policy are also the main feature of the market in freight transport. The railway freight market was opened earlier, and thus there have already been more new participants and the competition is sharp-edged; however, the volume of goods transport has been decreasing. This pertains to Poland, which ranks among the most attractive markets in the V4, and also in the EU. Nevertheless, inter-modal competition has appeared only in the Czech Republic.

The passenger railway markets of the V4 would be quite attractive, but the legal environment does not allow market entry, such as the attempt of Arriva in the Czech Republic. Some other national passenger railway operators would also be takeover targets, but they are state protected, which is the case even in aviation. There is a strong need for external fund allocation, thus expansions could continue in the form of franchise and mergers such as Rail Cargo Austria privatizing MÁV Cargo or DB Schenker in turn taking over PCC Rail SA. This would also be a solution for the passenger service, which is suffering from a lack of funding. The new organizational framework could renew thinking and also renew the actual mechanisms of the companies, which should lead to enhanced effectiveness, competitiveness and consumer benefits, thus increasing modal split.

From the supplier point of view, private capital inflows, modernization and increased operational efficiency are the main benefits of deregulation. Looking at the situation from the point of view of demand, there is a significant advantage in having the possibility to choose among operators, and in particular, the improving service quality that these new operators provide.

Only a further coherent strategy can lead to full liberalization. In line with sustainable development and also the EU's aspiration, without such liberalization, the decline in demand of rail track usage cannot be stemmed, and moreover, effective and competitive national and international markets will not be nurtured.

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Effect of Surface Roughness on the Behavior of a Magnetic Fluid-based Squeeze Film between Circular Plates with Porous Matrix of Variable Thickness

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Abstract: An endeavor has been made to investigate the performance of a magnetic fluid based squeeze film between rough circular plates while the upper plate has a porous facing of variable porous matrix thickness. The bearing surfaces are transversely rough. The random roughness of the bearing surfaces is characterized by a random variable with non-zero mean, variance and skewness. The associated Reynolds' equation is stochastically averaged with respect to the random roughness parameter and is solved with appropriate boundary conditions. The results for bearing performance characteristics such as pressure, load carrying capacity and response time for different values of mean, standard deviation and measure of symmetry are numerically computed and presented graphically. First of all it is observed that these performance characteristics increase with the increasing magnetization parameter thereby, suggesting that the performance of the bearing with magnetic fluid lubricant is better than that with the conventional lubricant. It is noticed that the bearing suffers owing to transverse surface roughness. However, the negatively skewed roughness tends to increase the load carrying capacity. Moreover, there is a very significant observation that with a proper selection of the thickness ratio parameter a magnetic fluid based squeeze film bearing with variable porous matrix thickness in the case of negatively skewed roughness can be made to perform considerably better than that of a conventional porous bearing with an uniform porous matrix thickness working with a conventional lubricant. In addition, this article makes it clear that by choosing properly the thickness ratio parameter and the strength of the magnetic field, the adverse impact induced by roughness on the bearing system can be minimized in the case of negatively

skewed roughness especially when negative variance occurs. Thus, this study makes it mandatory to account for roughness while designing the bearing system.

Keywords: magnetic fluid; squeeze film; transverse roughness; Reynolds' equation; variable film thickness; load carrying capacity

Nomenclature:

a	Radius of the circular plate (mm)
h	Uniform film thickness (mm)
H	Porous wall thickness (mm)
$\overline{M}$	Oblique magnetic field (Gauss)
p	Pressure distribution (N/mm^2)
P	The pressure in the porous matrix (N/mm^2)
w	Load carrying capacity (N)
k	As defined in [6] (Thickness ratio parameter)
μ	Dynamic viscosity of the lubricant ($N.s/mm^2$)
ϕ	Permeability of the porous matrix (Col^2kgm/s^2)
θ	Inclination of the magnetic field (Radians)
σ	Standard deviation (mm)
α	Variance (mm)
ε	Skewness (mm^3)
ΔT	Dimensionless squeeze time
μ_0	Permeability of the free space (N/A^2)
H_0	Porous wall thickness at r = 0 (mm)
H_1	Porous wall thickness at r = a (mm)
$\overline{p}$	Dimensionless pressure
$\overline{W}$	Load carrying capacity in dimensionless form
$\overline{\mu}$	Magnetic susceptibility (mm^3/kg)
μ^*	Magnetization parameter
$\boldsymbol{\sigma}$	Standard deviation in dimensionless form
$\boldsymbol{\alpha}$	Variance in dimensionless form
$\boldsymbol{\varepsilon}$	Skewness in dimensionless form

1 Introduction

The squeeze film behavior between non porous plates was analyzed by Archibald (1956). Of course, the porous bearings have been used for a quite long time, the theoretical analysis of such bearings have various advantages over conventional non-porous bearings. For instance, porous bearings can run hydrodynamically for a longer time without maintenance and are more stable than the equivalent conventional bearings. Murti (1974) considered the squeeze film behavior between two circular disks, when one of them has a porous facing press fitted into a solid wall. The analysis of this investigation was much simplified by Prakash and Vij (1973) by incorporating the Morgan Cameron approximation, when the

porous facing thickness is assumed small. It is well known that the introduction of a sintered porous bush in the bearing results in loss of mechanical strength and reduction of film pressure and, consequently, in load carrying capacity.

All the above analyses investigating the porous bearings, considered the wall thickness to be uniform. However, in reality the porous facing may not be of uniform thickness due to various manufacturing reasons; for instance, the non uniform application of pressure while sintering may lead to a non uniform thickness of porous bush. But the non uniformity of the thickness of porous bush gives rise to an additional degree of freedom for its design. The degree of freedom is nothing but the choice of the value of the porous thickness ratio parameter for the bearing. Therefore, the design consideration of the bearing may also dictate the choice of non uniform wall thickness of the porous housing. The effect of the variable thickness of the porous matrix on the performance of a squeeze film behavior between porous circular plates was analyzed by Prajapati (1995). The above investigations considered conventional lubricant. Verma (1986) and Agrawal (1986) dealt with the application of magnetic fluid as a lubricant. They observed that the bearing system registered an improved performance. Subsequently, Bhat and Deheri (1993) studied the squeeze film between porous annular disks using a magnetic fluid lubricant with the external magnetic field oblique to the lower disk. Also, Bhat and Deheri (1991, 1993) investigated the performance of the magnetic fluid based squeeze film behavior in curved porous circular disks. Prajapati (1995) studied the effect of axial current pinch on squeeze film between circular plates with lubricant inertia adopting momentum integral method. Patel, Deheri and Vadher (2010) discussed the performance of a magnetic fluid based short bearing and established the importance of magnetic fluid lubricant for extending the life period of the bearing system. By now, it is well known that the bearing surfaces particularly, after having some run-in and wear, develop roughness. In order to study and analyze the effect of surface roughness on the performance of squeeze film bearings, various methods have been employed. Several investigators have proposed a stochastic approach to mathematically model the random character of the roughness (Tzeng and Saibel (1967), Christensen and Tonder (1969a, 1969b 1970)). Christensen and Tonder (1969a, 1969b 1970) presented a comprehensive general analysis for both transverse as well as longitudinal surface roughness based on a general probability density function by developing and modifying the approach of Tzeng and Saibel (1967). Subsequently, this approach of Christensen and Tonder (1969a, 1969b, 1970) laid down the basis for investigating the effect of surface roughness in a number of investigations (Ting (1975), Prakash and Tiwari (1983), Prajapati (1992), Guha (1993), Gupta and Deheri (1996)). Andharia, Gupta and Deheri (1997, 1999) discussed the effect of surface roughness on the performance of a squeeze film bearing using a general stochastic analysis [without making use of a specific probability distribution] for describing the random roughness.

Deheri, Patel and Patel (2006) dealt with the behavior of magnetic fluid-based squeeze film between porous circular plates with a porous matrix of variable thickness. Here a significant observation was made that with the proper selection of thickness ratio parameter, a magnetic fluid-based squeeze film bearing with variable porous matrix can be made to perform considerably better than that of a conventional porous bearing with a uniform porous matrix thickness working with a conventional lubricant. It has been sought to discuss the effect of transverse surface roughness on the geometry and configurations of Deheri, Patel and Patel (2006).

2 Analysis

The configuration of the bearing system is presented below, which considers the laminar axisymmetric flow of an incompressible fluid between two parallel circular plates of radius a. The lower one is fixed while the upper plate has a porous facing of variable porous matrix thickness backed by a solid wall.

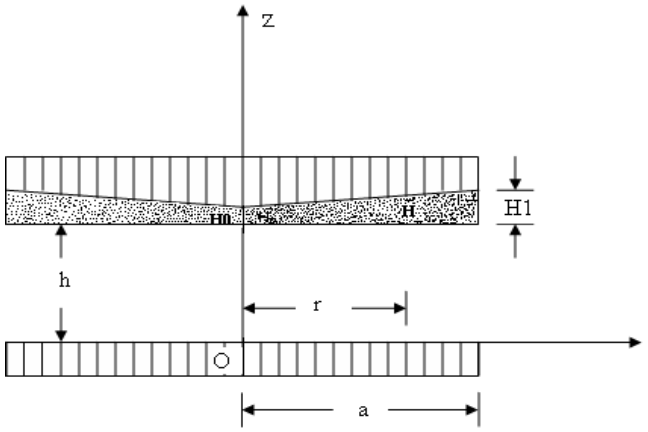

Figure 1
Configuration of the bearing system

The upper plate approaches the lower one normally with velocity $\dot{h} = \frac{dh}{dt}$; where h is the uniform film thickness. The porous wall thickness is assumed to vary linearly with its value at r = 0 as H_0 while this value is H_1 at r = a. Consequently, the porous wall thickness H is given by

$$H = H_0 + (H_1 - H_0)\left(\frac{r}{a}\right) \tag{1}$$

The Z – axis is taken normal to the lubricant film.

The bearing surfaces are assumed to be transversely rough. Following the discussions of Christensen and Tonder (1969a, 1969b, 1970) regarding the stochastic modeling of roughness the actual film thickness is given by

$$h = \bar{h} + h_s(\xi)$$

where $\bar{h}$ is the mean film thickness and is given by (Pinkus and Sternlicht (1961))

$$\bar{h} = C_r(1 - E_c\cos\gamma)$$

wherein, C_r is the radial clearance, E_c is the eccentricity ratio e / C_r and e the eccentricity of the bearing. h_s measured from the nominal mean level of the bearing surface and ξ is the random variable characterizing the roughness of the bearing surfaces. In general h_s may not be symmetric in nature. h_s is considered to be stochastic in nature and governed by the probability density function $f(h_s)$, $-c \le h_s \le c$ where c is the maximum deviation from the mean film thickness. The mean α, the standard deviation σ and the parameter ε which is the measure of symmetry of the random variable h_s are defined by the relationships

$$\alpha = E(h_s),$$

$$\sigma^2 = E[(h_s - \alpha)^2]$$

and

$$\varepsilon = E[(h_s - \alpha)^3]$$

where E denotes the expected value defined by

$$E(R) = \int_{-c}^{c} R f(h_s)\,dh_s$$

while,

$$f(h_s) = \begin{cases} \dfrac{35}{32c^7}(c^2 - h_s^2)^3, \text{if } -c \le h_s \le c \\ 0, \text{elsewhere} \end{cases}$$

Assuming axially symmetric flow of the magnetic fluid between the plates under an oblique magnetic field $\bar{M} = [M(r)\cos\theta, 0, M(r)\sin\theta]$ whose magnitude vanishes at r = 0 and r = a, following the analysis of Prajapati (1995) the concerned Reynolds' equation governing the film pressure is obtained as [c.f. Bhat and Deheri (1993)].

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rg(h)\frac{d}{dr}(p-0.5\mu_0\bar{\mu}M^2)\right)=12\mu\left[\dot{h}-\frac{\phi}{\mu}\left(\frac{\partial}{\partial z}(p-0.5\mu_0\bar{\mu}M^2)\right)_{z=h}\right] \quad (2)$$

where

$$M^2 = r(a-r),$$

and

$$g(h) = h^3+3\sigma^2h+3h^2\alpha+3h\alpha^2+3\sigma^2\alpha+\alpha^3+\varepsilon$$

μ is the fluid viscosity, $\bar{\mu}$ represents the magnetic susceptibility, μ_0 stands for the permeability of the free space and ϕ is the permeability of the porous housing and p(r, z) is the pressure in the porous matrix governed by the Laplace's equation [c.f. Prajapati (1995), Bhat and Deheri (1993) Prakash and Vij (1973.b)] which assumes the following form in view of the Appendix - B

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}(p-0.5\mu_0\bar{\mu}M^2)\right)+\frac{\partial^2}{\partial z^2}(p-0.5\mu_0\bar{\mu}M^2)=0 \quad (3)$$

The associated boundary conditions for solving equations 2 and 3 are

$$p = 0 \text{ at } r = 0, a$$

$$P = 0 \text{ at } r = 0, a$$

$$p = P \text{ at } z = h$$

and

$$\frac{\partial p}{\partial z}=0 \text{ at } z=h+H \quad (4)$$

The physical meaning and the related significance of these boundary conditions are explained in Prajapati (1994). The system 2-4 appears to be coupled both in terms of differential equation as well as boundary conditions. To obtain its solution, we first uncouple the system by making use of the simplifying assumption that H may be considered so small that a Taylor's series representations may be used. This results in the uncoupled modified Reynolds equation as

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}(p-0.5\mu_0\bar{\mu}M^2)\right)=\frac{12\mu\dot{h}}{(h^3+3\sigma^2h+3h^2\alpha+3h\alpha^2+3\sigma^2\alpha+\alpha^3+\varepsilon+12\phi H)} \quad (5)$$

Introducing the dimensionless quantities

$$\mu^* = -\frac{\mu_0 \bar{\mu} \bar{h}^3}{\mu \dot{h}}, \quad \bar{r} = \frac{r}{a}, \quad \bar{p} = -\frac{h^3 p}{\mu \dot{h} a^2}, \quad \bar{H} = \frac{H}{H_0} = 1 + k\bar{r}, \quad \psi = \frac{\psi_0}{\bar{h}^3},$$

$$\psi_0 = \frac{\phi H_0}{h_0^3}, \qquad \bar{h} = \frac{h}{h_0}, \qquad \sigma = \frac{\sigma}{h} \qquad \alpha = \frac{\alpha}{h} \qquad \varepsilon = \frac{\varepsilon}{h^3} \tag{6}$$

where

$$k = \frac{H_1}{H_0} - 1$$

and h_0 is the initial film thickness; one obtains the differential equation for the pressure in dimensionless form

$$\frac{1}{\bar{r}} \frac{d}{d\bar{r}} \left(\bar{r} \frac{d}{d\bar{r}} (\bar{p} - 0.5\mu^* \bar{r}(1-\bar{r})) \right) = \frac{-12}{G(h) + 12\psi(k\bar{r} + 1)} \tag{7}$$

where

$$G(h) = 1 + 3\sigma^2 + 3\alpha + 3\alpha^2 + 3\sigma^2\alpha + \alpha^3 + \varepsilon$$

Owing to the boundary conditions

$$\frac{d\bar{p}}{d\bar{r}} = 0 \text{ at } \bar{r} = 0$$

and

$$\bar{p} = 0 \text{ at } \bar{r} = 1$$

the solution of equation (7) is given by

$$\bar{p} = 0.5\,\mu^* \bar{r}(1-\bar{r}) - \frac{1}{\psi k} \int_1^{\bar{r}} \left[1 - \frac{\ln(b\bar{r} + 1)}{b\bar{r}} \right] d\bar{r} \tag{8}$$

where

$$b = \frac{12\psi k}{G(h) + 12\psi}$$

Next, the load carrying capacity of the bearing

$$w = 2\pi \int_0^a r p(r) dr$$

in dimensionless form is found to be

$$W = -\frac{wh^3}{\mu\dot{h}a^4} = \frac{\pi\mu^*}{12} + \frac{\pi}{\psi k}\left[\frac{1}{3} - \frac{1}{2b}\left\{\ln(b+1)\left(1-\frac{1}{b^2}\right) - \frac{1}{2} + \frac{1}{b}\right\}\right] \tag{9}$$

If the time taken for the plate to move from the film thickness $h = h_0$ to $h = h_1$ then the non dimensional squeeze time ΔT is derived from equation (9) as

$$\Delta T = \frac{wh_0^2}{\mu a^4}\int_0^{t_1} dt = -\int_{\bar{1}}^{\bar{h}0} \frac{W}{\bar{h}^3} d\bar{h} \tag{10}$$

3 Results and Discussion

It is observed from equations 8, 9 and 10 that the dimensionless pressure, load carrying capacity and squeeze time depend on the magnetization parameter μ^*, roughness parameters σ, α, ε and the thickness ratio parameter k. The results for uniform porous matrix thickness are obtained by taking thickness ratio parameter k to be zero (Appendix A: Case – 2). When ψ is assumed to be zero, the results for the conventional non porous magnetic fluid-based squeeze film bearings are obtained (Appendix A: Case – 1). Furthermore, the corresponding non magnetic case is obtained by setting μ^* to be zero. From equation 9 it is evident that the load carrying capacity increases by $\pi\mu^*/12$.

The variation of load carrying capacity with respect to magnetization parameter μ^* for different values of porosity ψ, roughness parameters σ, α, ε and the thickness ratio k is presented in Figures 2-6 respectively. From these figures it is noticed that the performance of the present bearing system is relatively better than that with a conventional lubricant as the load carrying capacity increases with increasing magnetization parameter μ^*. The load carrying capacity decreases with increasing values of ψ (Figure 2) and also with increasing values of σ, α, ε (Figures 3-5). It can be easily observed from Figure 6 that the load carrying capacity decreases with the increasing values of the thickness ratio parameter k.

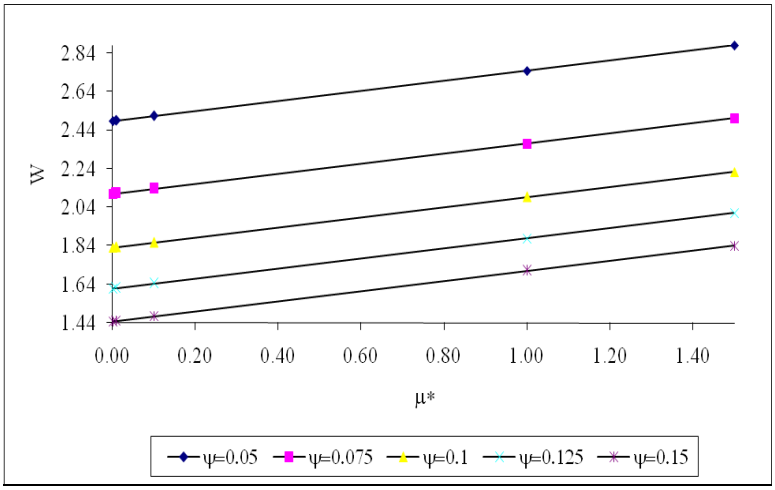

Figure 2
Variation of load carrying capacity with respect to μ* and ψ

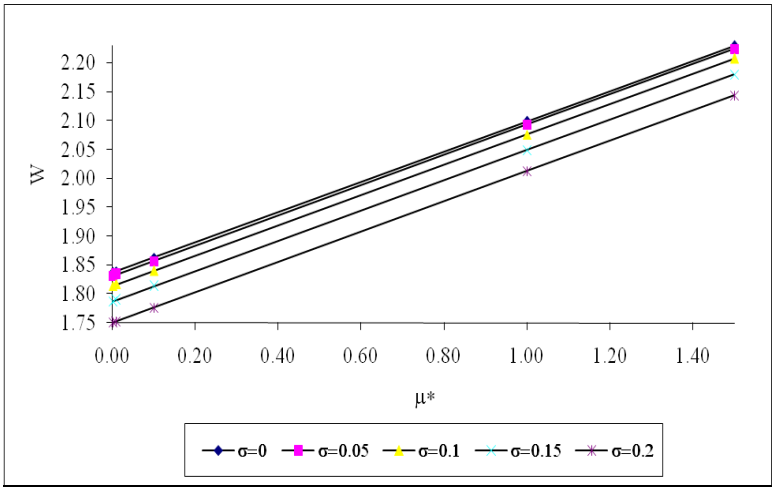

Figure 3
Variation of load carrying capacity with respect to μ* and **σ**

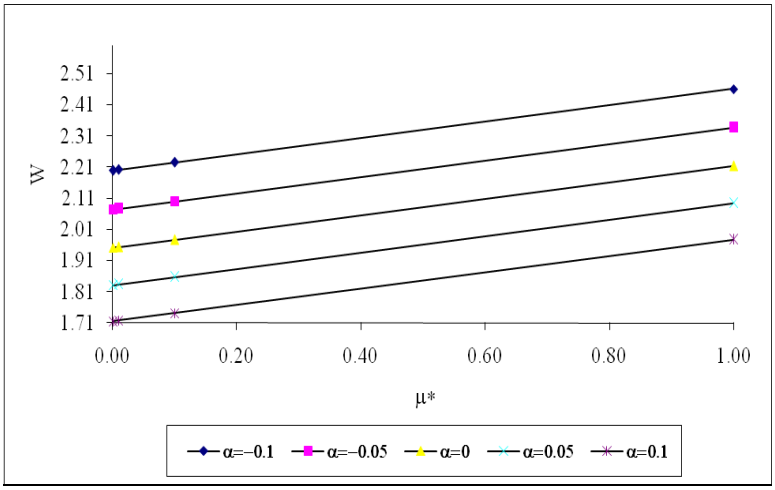

Figure 4
Variation of load carrying capacity with respect to μ* and **α**

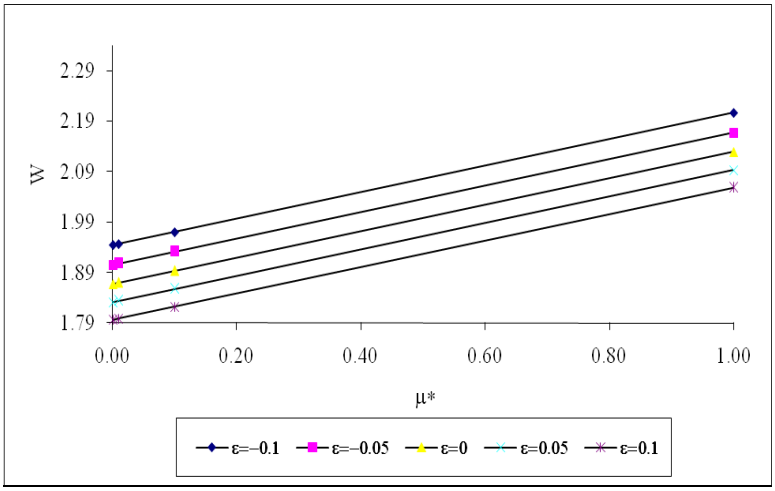

Figure 5
Variation of load carrying capacity with respect to μ* and **ε**

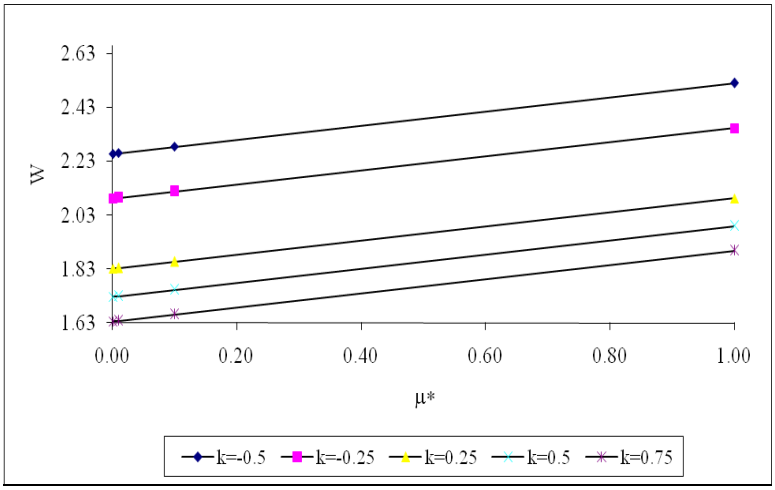

Figure 6
Variation of load carrying capacity with respect to μ* and k

We have the distribution of load carrying capacity with respect to ψ for various values of **σ, α**, **ε** and the thickness ratio k presented in Figures 7-10. It is observed that the load carrying capacity increases with decreasing values of the roughness parameters. The decrease in the load carrying capacity due to porosity ψ and skewness **ε** (+ve) gets further decreased by the variance **α** (+ve). Here, it is noted that the role of positive **ε** in decreasing the load carrying capacity is equally sharp.

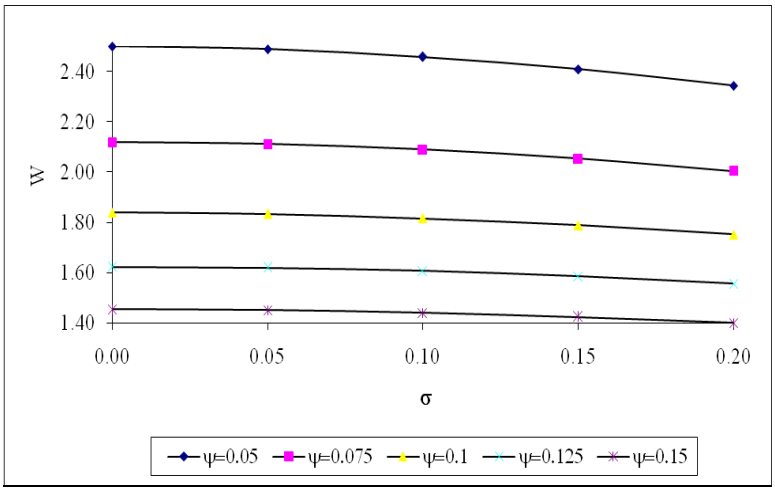

Figure 7
Variation of load carrying capacity with respect to ψ and **σ**

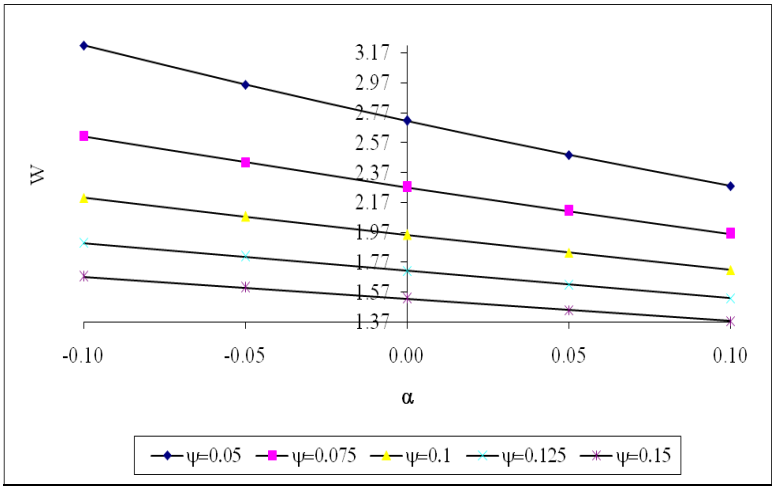

Figure 8
Variation of load carrying capacity with respect to ψ and **α**

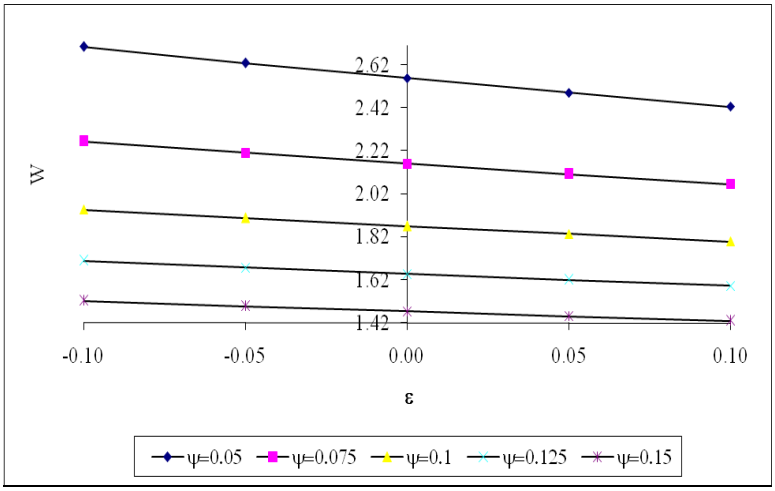

Figure 9
Variation of load carrying capacity with respect to ψ and **ε**

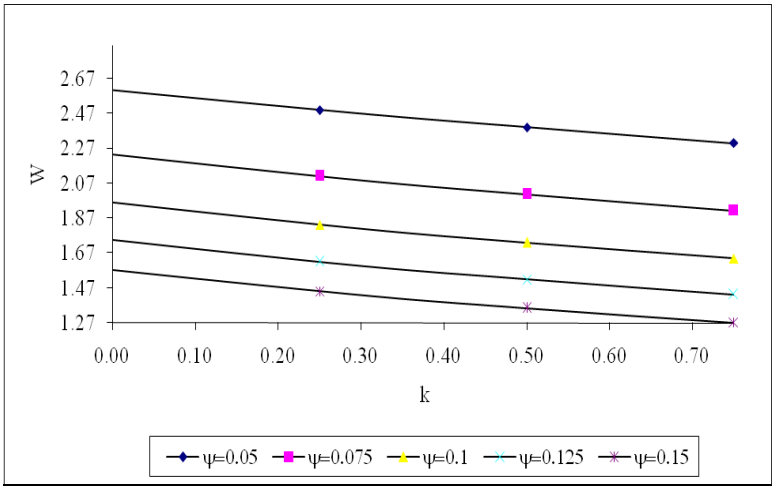

Figure 10

Variation of load carrying capacity with respect to ψ and k

The distribution of load carrying capacity with respect to **σ** for different values of **α, ε** and the thickness ratio k is given in Figures 11-13. From these figures it is seen that the load carrying capacity decreases significantly with increasing values of **α**, **ε** and k wherein even the thickness ratio plays a crucial role in the reduction of load carrying capacity.

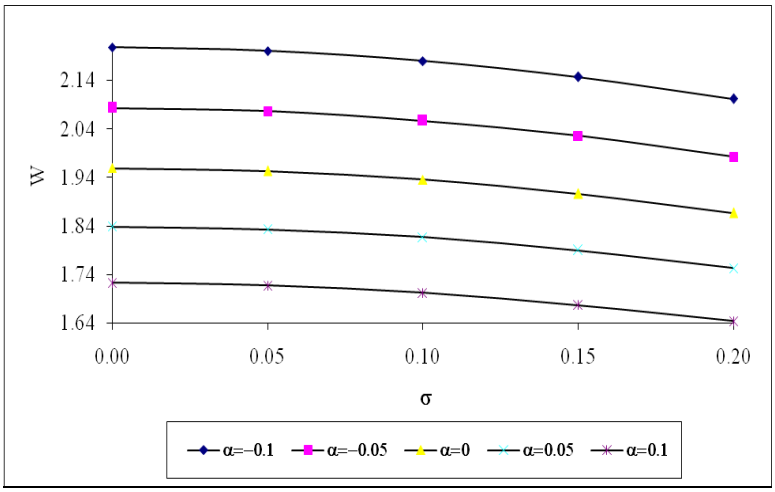

Figure 11

Variation of load carrying capacity with respect to **σ** and **α**

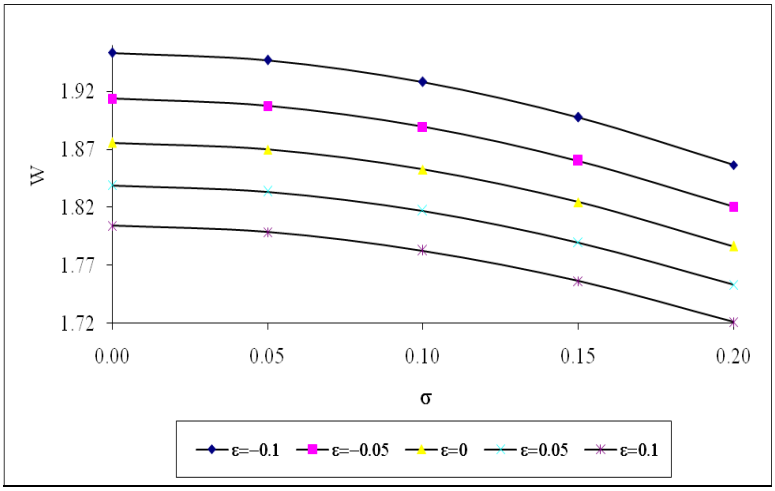

Figure 12
Variation of load carrying capacity with respect to **σ** and **ε**

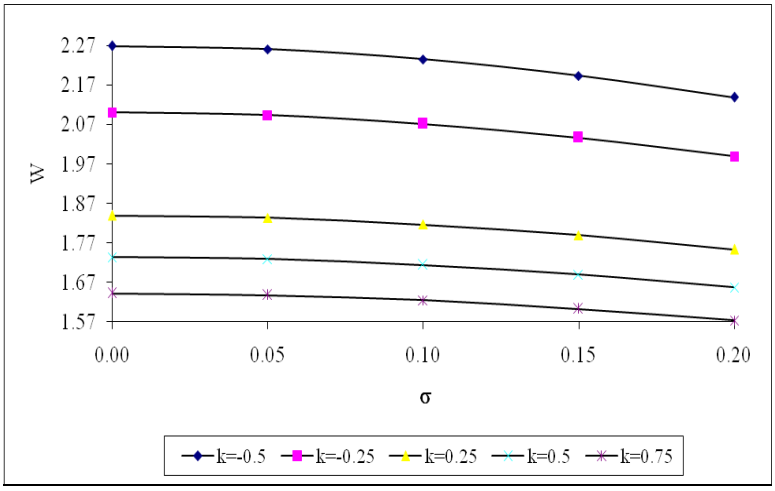

Figure 13
Variation of load carrying capacity with respect to **σ** and k

Lastly, the combined effect of **ε** and **α** on the distribution of load carrying capacity is presented in Figures 14-16. It is noticed that negatively skewed roughness tends to enhance the performance of the bearing system which, in turn, gets further increased when negative variance is involved.

It is clearly seen from equation 10 that the squeeze time almost follows the trends of the load carrying capacity.

A close look at some of these figures reveals that by suitably choosing the thickness ratio parameter k, the porosity ψ and standard deviation σ induced negative effect can be neutralized substantially by the positive effect introduced by the magnetization parameter μ^* in the case of negatively skewed roughness.

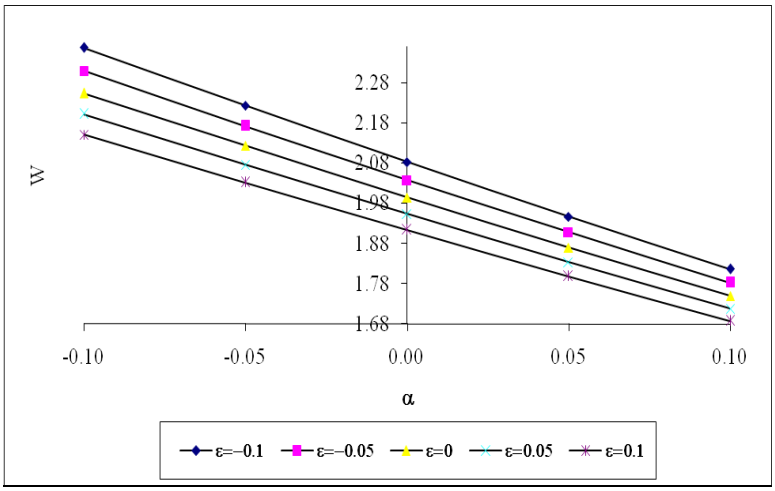

Figure 14
Variation of load carrying capacity with respect to α and ε

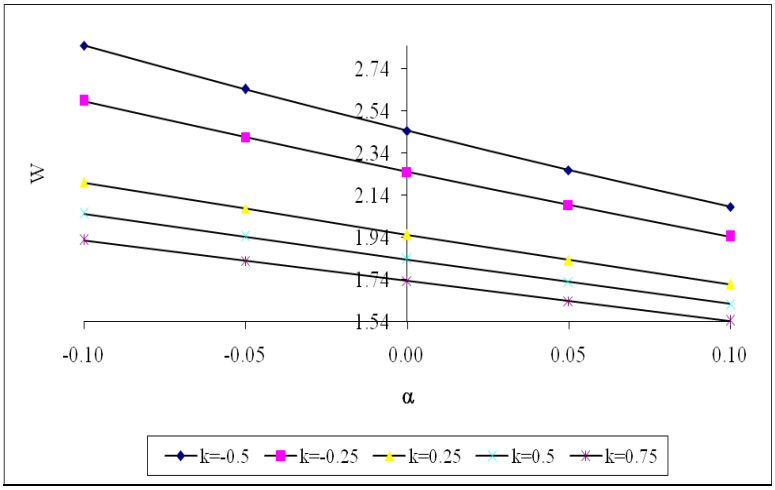

Figure 15
Variation of load carrying capacity with respect to α and k

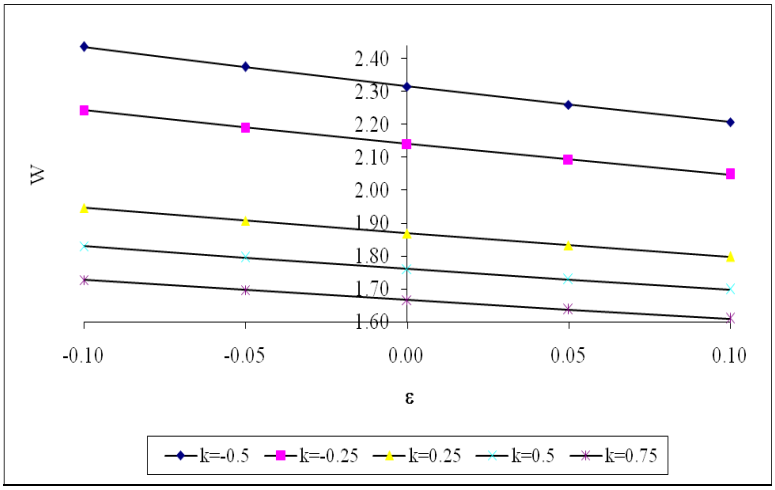

Figure 16
Variation of load carrying capacity with respect to **ε** and k

Conclusions

It is found that the bearing system can support a load even when there is no flow. In addition, a very significant observation is that, with a proper selection of the thickness ratio, a magnetic fluid based squeeze film bearing with variable porous matrix thickness can be made to perform considerably better than a porous bearing working with a conventional lubricant with a uniform porous matrix thickness. Although, the thickness ratio parameter provides an additional degree of freedom from a design point of view, the roughness must be duly accounted for while designing the bearing system from the bearing's life period point of view.

Acknowledgements

The critical in-depth comments and fruitful lucid suggestions of the referees and editors leading to the overall improvement in the presentation of the paper are gratefully acknowledged. We put on record our sincere thanks for the funding of U. G. C. major research project (U. G. C. F. No. 32-143/2006 (SR) – "Magnetic fluid based rough bearings") under which this investigation has been carried out.

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Appendix: A

Case: 1 When $\psi = 0$ the concerned Reynolds' equation becomes

$$\frac{1}{\bar{r}}\frac{d}{d\bar{r}}\left(\bar{r}\frac{d}{d\bar{r}}(\bar{p}-0.5\mu^{*}\bar{r}(1-\bar{r}))\right)=-\frac{12}{G(h)}$$

Solution of this equation with the boundary conditions

$$\frac{d\bar{p}}{d\bar{r}} = 0 \text{ at } \bar{r} = 0$$

and

$$\bar{p} = 0 \text{ at } \bar{r} = 1$$

yields the pressure in non-dimensional form as

$$\bar{p} = 0.5\,\mu^{*}\bar{r}(1-\bar{r}) + \frac{3(1-\bar{r}^{2})}{G(h)}$$

Notice that the pressure is independent of k.

Then the load carrying capacity of the bearing

$$w = 2\pi \int_0^a rp(r)dr$$

in dimensionless form is obtained as

$$W = -\frac{wh^3}{\mu \dot{h} a^4} = \pi \left[\frac{\mu^*}{12} + \frac{3}{2(G(h))} \right]$$

Case: 2 When k = 0 the associated Reynolds' equation turns out to be

$$\frac{1}{\bar{r}} \frac{d}{d\bar{r}} \left(\bar{r} \frac{d}{d\bar{r}} (\bar{p} - 0.5\mu^* \bar{r}(1-\bar{r})) \right) = \frac{-12}{G(h) + 12\psi}$$

Solution of this equation with the boundary conditions

$$\frac{d\bar{p}}{d\bar{r}} = 0 \text{ at } \bar{r} = 0$$

and

$$\bar{p} = 0 \text{ at } \bar{r} = 1$$

turns in the pressure in non-dimensional form as

$$\bar{p} = 0.5\,\mu^* \bar{r}(1-\bar{r}) + \frac{3(1-\bar{r}^2)}{G(h) + 12\psi}$$

Then the load carrying capacity of the bearing

$$w = 2\pi \int_0^a rp(r)dr$$

in dimensionless form is calculated as

$$W = -\frac{wh^3}{\mu \dot{h} a^4} = \pi \left[\frac{\mu^*}{12} + \frac{3}{2(G(h) + 12\psi 2} \right]$$

From these two cases it is also, observed that for $\psi < 0.0416$ a squeeze film with uniform film thickness performs better than that of a non porous squeeze film with variable film thickness.

Appendix: B

Neuringer and Rosenweig (1964) proposed a simple model to describe the steady flow of magnetic fluid in then presence of slowly changing external magnetic fields. The model consists of the following equations:

$$\rho\left(\bar{q}\bullet\nabla\right)\bar{q} = -\nabla p + \eta\nabla^2\bar{q} + \mu_0\left(\overline{M}\bullet\nabla\right)\overline{H} \tag{A$_1$}$$

$$\nabla\bullet\bar{q} = 0 \tag{A$_2$}$$

$$\nabla\times\overline{H} = 0 \tag{A$_3$}$$

$$\overline{M} = \bar{\mu}\overline{H} \tag{A$_4$}$$

$$\nabla\bullet\left(\overline{H}+\overline{M}\right) = 0 \tag{A$_5$}$$

where ρ is the fluid density, $\bar{q} = (u, v, w)$ is the fluid velocity in the film region, p is the film pressure, η is the fluid viscosity, μ_0 is the permeability of free space, $\overline{M}$ is the magnetization vector, $\overline{H}$ is the external magnetic field and $\bar{\mu}$ is the magnetic susceptibility of the magnetic particles.

Using equations $(A_3) - (A_4)$, equation (A_1) becomes

$$\rho\left(\bar{q}\bullet\nabla\right)\bar{q} = -\nabla\left(p - \frac{\mu_0\bar{\mu}}{2}H^2\right) + \eta\nabla^2\bar{q}$$

This shows that an extra pressure $\frac{1}{2}\mu_0\bar{\mu}H^2$ is introduced into the Navier-Stokes equations when magnetic field is used as lubricant. Thus, the modified Reynolds equation in this case is obtained as

$$\frac{\partial}{\partial x}\left[h^3\frac{\partial}{\partial x}\left(p - \frac{1}{2}\mu_0\bar{\mu}H^2\right)\right] + \frac{\partial}{\partial y}\left[h^3\frac{\partial}{\partial y}\left(p - \frac{1}{2}\mu_0\bar{\mu}H^2\right)\right] = 6\eta U\frac{\partial h}{\partial x} + 12\eta W_h \tag{A$_6$}$$

But the modified Reynolds equation for non-porous bearings in cylindrical polar co-ordinates is derived by Bhat (2003) is expressed as

$$\frac{1}{r}\frac{d}{dr}\left(rh^3\frac{dp}{dr}\right) = 12\eta\dot{h}_0$$

Thus, the modified Reynolds equation associated with magnetic fluid in view of (A_6) turns out to be

$$\frac{1}{r}\frac{d}{dr}\left[rh^3\frac{d}{dr}\left(p - \frac{\mu_0\bar{\mu}H^2}{2}\right)\right] = 12\eta\dot{h}_0$$

The Dynamic Economic Dispatch including Wind Power Injection in the Western Algerian Electrical Power System

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Abstract: In this paper, we investigate the effect of the injection of wind farm energy in the western Algerian electrical power system on Dynamic Economic Dispatch (DED). DED is solved by Harmony Search algorithm (HS). HS is a newly-developed meta-heuristic algorithm that uses a stochastic random search. It is simple in concept, few in parameters and easy in implementation. The simulations are realized by considering first the western Algerian power system as it is (WA: 2003 data), then the western Algerian electrical power system with the injection of wind farm energy (Western Algerian power system + Wind energy WAW). The results are compared in production cost and harmful emissions (CO_2). After a theoretical introduction of the problem formulation and the harmony search algorithm, a description of the site and the wind farm is presented, followed by a discussion of the simulation results.

Keywords: optimization; harmony search; dynamic economic dispatch; wind power; CO_2 emission

1 Introduction

The rise of environmental protection and the progressive exhaustion of traditional fossil energy sources have increased the interests in integrating renewable energy sources into existing power systems [1]. Wind power generation is becoming more and more popular while the large-scale wind farm is the mainstream one. It has the potential benefits of cutting the consumption of irreplaceable fuel reserves and reducing pollutants and harmful emissions as the demand for electricity has steadily rises due to industrial developments and economic growth in most parts of the world [2].

Economic dispatch is one of the most important optimization problems in power system operation and forms the basis of many application programs. The main objective of economic load dispatch of electric power generation is to schedule the

committed generating unit outputs so as to meet the load demand at minimum operating cost while satisfying all unit and system constraints [3]. Because the output of wind power depends on the wind speed, which is related to climatological and micrometeorological parameters, wind behavior is quite distinct from conventional energy operation at their rated capacities [4].

In this paper we investigate the effect of introducing a wind power farm in to the western Algerian electrical power system. This can be expressed as a Dynamic Economic Dispatch (DED) problem solved with Harmony Search Algorithm [5].

2 Problem Formulation

2.1 Wind Farm Output Calculation

To simulate the wind farm as an equal wind turbine, all wind speeds and directions of wind turbines in one farm are assumed to be the same. The relationship between the wind turbine output P_W and the wind speed V_W can be expressed as a subsection function [4, 6, 7]:

$$P_W = \begin{cases} 0 & V_W < V_{CI} \\ \frac{1}{2} C_P.\rho.\pi.R_P^2.V_W^3 & V_{CI} \le V_W < V_R \\ P_R & V_R \le V_W < V_{CO} \\ 0 & V_W \ge V_{CO} \end{cases} \quad (1)$$

where C_P is the aerodynamic coefficient of turbine power, ρ is the air density (1,225 kg/m^3), R_P the turbine ray, V_{CI}, V_R and V_{CO} are respectively the cut-in, the rated and the cut-out wind speeds. P_R is the rated output of the wind turbine. The C_P coefficient cannot, theoretically, pass the limit of Betz (C_{p_limit}= 0.593) [8].

2.2 Economic Dispatch

In the practical cases, the total fuel cost may be represented as a polynomial function of real power generation [9]:

$$F(P_{Gi}^t) = \sum_{i=1}^{ng} (a_i P_{Gi}^{t\ 2} + b_i P_{Gi}^t + c_i) \quad (2)$$

where F is the total fuel cost of the system at time t, P^t_{Gi} is real power output of the i-th unit at time t, ng is the number of generators including the slack bus, a_i, b_i and c_i are the cost coefficients of the i-th unit.

The daily total cost of active power generation may be expressed by:

$$G(P_{Gi}^t) = \sum_{t=1}^{24} \sum_{i=1}^{ng} F(P_{Gi}^t) \tag{3}$$

The Economic Dispatch Problem can be mathematically represented as:

Minimise $G(P_{Gi}^t)$ (4)

under constraints:

$$\sum_{i=1}^{ng} P_{Gi}^t + P_W^t - P_D^t - P_L^t = 0 \tag{5}$$

$$P_{Gi\min} \le P_{Gi}^t \le P_{Gi\max} \quad i = 1,..., ng \tag{6}$$

where $P^t{}_L$ and $P^t{}_D$ are the real power losses and the total demand at time t. P_{Gimin} and P_{Gimax} are the generation limit of the i-th unit.

The real power losses are a function of real power injection $P^t{}_i$ and reactive power Q_i and voltage nodes [10, 11]. Their expression is given by:

$$P_L(P_{Gi}^t) = \sum_{\substack{i=1 \\ j=1}}^{n} [a_{ij}(P_i^t P_j^t + Q_i Q_j) + b_{ij}(Q_i P_j^t - P_i^t Q_j)] \tag{7}$$

where $a_{ij} = \dfrac{r_{ij}}{|V_i|.|V_j|}\cos(\theta_{ij})$, $b_{ij} = \dfrac{r_{ij}}{|V_i|.|V_j|}\sin(\theta_{ij})$,and r_{ij} are the real components of bus impedance matrix.

The voltage nodes V_i (in module $|V_i|$ and phase θ_i) and the reactive power injection are assumed constant. In this case, the power transmission losses can be expressed in terms of active power generations by assuming that the demand for power remains constant during dispatch period. This expression is given by:

$$P_L(P_{Gi}^t) = \sum_{\substack{i=1 \\ j=1}}^{n} a_{ij} P_{Gi}^t P_{Gj}^t - 2\sum_{\substack{i=1 \\ j=1}}^{n} (b_{ij} Q_j + a_{ij} P_{Di}^t) P_{Gi}^t + K^t \tag{8}$$

where

$$K^t = \sum_{\substack{i=1 \\ j=1}}^{n} [a_{ij}(P_{Di}^t P_{Dj}^t + Q_i Q_j) + b_{ij}(P_{Di}^t Q_j - Q_i P_{Dj}^t)]$$

3 The Harmony Search Algorithms

The HSA is inspired by the musical process of searching for a perfect state of harmony [5]. The optimization process, represented in Figure 1, is directed by four parameters:

1) Harmony Memory Size (HMS) is the number of solution vectors stored in Harmony Memory (HM).

2) Harmony Memory Considering Rate (HMCR) is the probability of choosing one value from HM and (1-HMCR) is the probability of randomly generating one new feasible value.

3) Pitch Adjusting Rate (PAR) is the probability of choosing a neighboring value of that chosen from HM.

4) Distance bandwidth (bw) defines the neighborhood of a value as [x^j ± bw*U(0,1)]. U(0,1) is a uniform distribution between 0 and 1.

Another intuitively important parameter is the Number of Iterations (NI) which is the stop criterion of many versions of HSA [12].

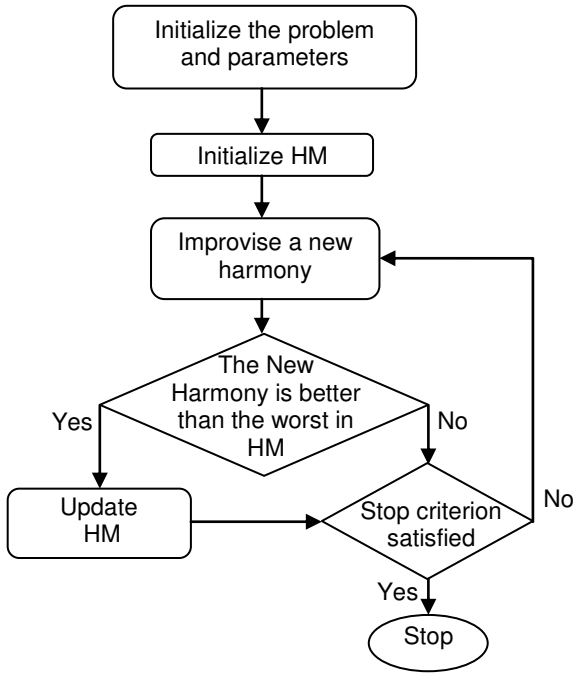

Figure 1
Optimization procedure of HSA

4 Application

4.1 Description of the Test System

The test system used in this paper is the western Algerian electrical power system 220 kV. The single-line diagram of this system is shown in Figure 2 and the detailed data are given in Reference [13]. The system is composed of 14 nodes with 3 power plants that are: power plant of "*Mersat El Hadjadj*" (node 1), power plant of "*Ravin Blanc*" (node 4) and power plant of "*Tiaret*" (node 3).

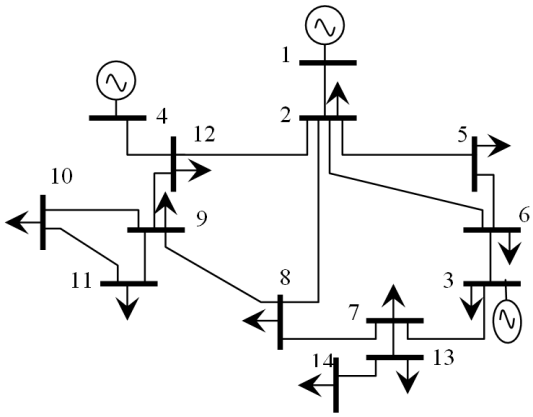

Figure 2
Topology of western Algerian electrical power system

Figure 3 (February 3, 2003) represents the daily load curve. The values of the Load Scaling Factor (LSF) are given in Figure 4 with a maximum value of 1.35 for the maximum load of 782 MW.

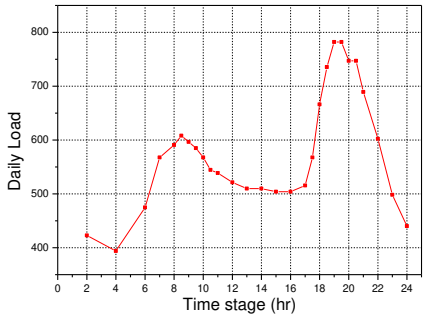

Figure 3
Daily Load

The coefficients of the transmission losses according to the powers generated for to the maximum load are:

$$a_{ij}=\begin{bmatrix} 0.00546 & -0.00052 & 0.00392 \\ -0.00052 & 0.01035 & -0.00137 \\ 0.00392 & -0.00137 & 0.01479 \end{bmatrix},\ -2\sum_{\substack{i=1\\ j=1}}^{n=1}(bijQ_j + aijP_{Dj}) = \begin{bmatrix} -0.02296 \\ 0.01680 \\ -0.03629 \end{bmatrix},\ K = 0.1032$$

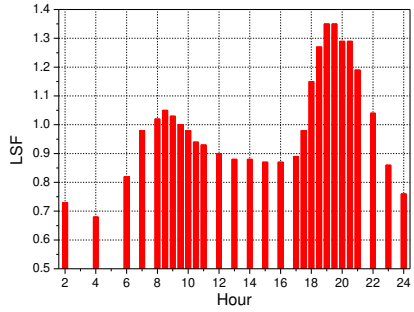

Figure 4
Load Scaling Factor

The cost functions [14, 15] providing the quantity of the fuel in Nm^3/h necessary to the production are:

$$F(P_{G1}^t) = 0.85\,P_{G1}^{t\,2} + 150P_{G1}^t + 2000$$

$$F(P_{G3}^t) = 0.4\,P_{G3}^{t\,2} + 75P_{G3}^t + 850$$

$$F(P_{G4}^t) = 1.7\,P_{G4}^{t\,2} + 250P_{G4}^t + 3000$$

Under the constraints:

$$30 \le P_{G1}^t \le 510\text{MW}$$

$$25 \le P_{G3}^t \le 420\text{MW}$$

$$10 \le P_{G4}^t \le 70\text{MW}$$

$$\sum_{i=1}^{ng} P_{Gi}^t + P_W^t - P_D^t - P_L^t = 0$$

4.2 Description of the Wind Farm

Figure 5 represents the map of the wind speed in Algeria to an altitude of 50 meters.

The map shows that the sites with the maximum wind speeds are those of *Adrar* (west south) and *Tiaret* (west north, in square) with a speed approaching 9 m/s and a recovered power density around 3.4 MWh/m^2 [16].

The site of *Tiaret* is chosen for the implant of the wind farm. This one is supposed composed of 20 identical wind turbines with 40 meters blades.

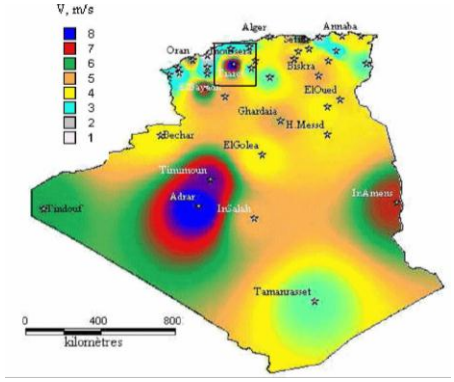

Figure 5
Atlas of wind speed at 50 m

Due to a lack of data, we use the curve of variation of the wind speed of February 03, 2010 [17]. This curve, after interpolation, is represented by Figure 6. The variations of the power produced by the wind farm, the production of the thermal power plants and the total demand with respect to the time stage are illustrated in Figure 7.

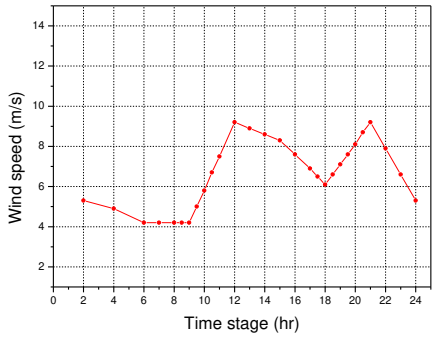

Figure 6
Daily variation of the wind speed

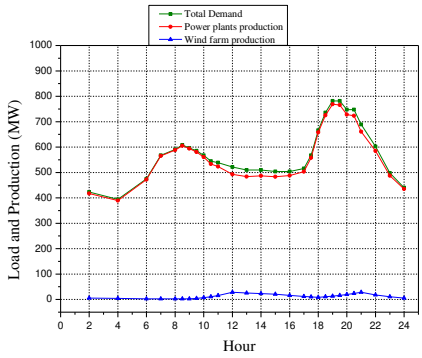

Figure 7
Power production and Load demand

4.3 Carbon Dioxide Emission

For the combustion, the emission of carbon dioxide can be calculated with good precision from a balance of the carbon contained in the fuel. The Lower Heating Value or Net Calorific Value (NCV) and the content in carbon of the fuel, necessary to this calculation, can be measured accurately.

The calculation of carbon dioxide emissions related to energy use of fuels includes five steps [18]:

a) determination of the amount (ton) of fuel consumed during a time T,

b) calculation of energy consumption from the quantity of fuel consumed and the NCV of the fuel,

c) calculation of the potential carbon emissions from energy consumption and carbon emission factors,

d) calculation of actual carbon oxidized from oxidation factors (correction for incomplete combustion),

e) conversion of carbon oxidized to CO_2 emissions.

Being of type H, The Algerian gas has the following characteristics:

$$\begin{cases} NCV = 49.6\ Gj/t \\ Density \quad \rho = 0.78\ Kg/m^3 \\ Carbon\ emission\ \ factor = 15.5\ Kg/Gj \\ Oxidation\ \ factor = 0.995 \end{cases}$$

For determining the amount of fuel consumed in one hour, it is necessary to convert the flow from Nm^3/h to m^3/h. The law of boyle-mariotte-lussac permits us to write, to equal pressures:

$$\frac{Nm^3/h}{273} = \frac{m^3/h}{(273+c^o)}, \tag{9}$$

which becomes for c°=20° : $m^3/h = 1.07\ Nm^3/h$

4.4 Results

The simulations are realized by considering first the western Algerian electrical power system as it is (WA), then the western Algerian electrical power system with the injection of wind farm energy (WAW).The results of the production cost, for the two cases WA and WAW are shown in Figure 8 and detailed in Table 1 and Table 2.

Table 1
Production costs (WA case)

time(hr)	Cost (Nm^3/h)	P_{G1}(MW)	P_{G3}(MW)	P_{G4}(MW)	P_L(MW)
2	94,939.463	100.726	302.774	20.938	1.579
4	85,895.721	92.58	286.017	16.864	1.566
6	112,235.482	115.428	332.947	28.292	1.674
7	146,253.725	141.711	386.65	41.439	2.127
8	155,422.338	148.315	400.097	44.743	2.311
8.5	162,475.972	153.278	410.19	47.225	2.471
9	157,756.749	149.969	403.461	45.57	2.362
9.5	153,077.708	146.62	396.731	43.894	2.193
10	146,253.725	141.711	386.65	41.439	2.127
10.5	137,352.701	135.121	373.214	38.143	1.974
11	135,168.813	133.476	369.856	37.32	1.94
12	128,716.808	128.544	359.785	34.853	1.849
13	124,498.056	125.261	353.073	33.211	1.796
14	124,498.056	125.261	353.073	33.211	1.796
15	122,413.518	123.62	349.718	32.39	1.772
16	122,413.518	123.62	349.718	32.39	1.772
17	126,599.384	126.902	356.429	34.032	1.822
17.5	146,253.725	141.711	386.65	41.439	2.127
18	187,636.984	185.498	420	63.338	2.688
18.5	223,575.384	248.624	420	70	2.965
19	252,192.443	295.355	420	70	3.355
19.5	252,192.443	295.355	420	70	3.355
20	230,370.734	260.288	420	70	3.044
20.5	230,370.734	260.288	420	70	3.044
21	198,755.638	202.065	420	70	2.746
22	160,108.117	151.623	406.825	46.397	2.416
23	120,345.149	121.98	346.363	31.57	1.75
24	100,559.131	105.62	312.83	23.387	1.6

Table 2
Production costs (WAW case)

time (hr)	Cost (Nm^3/h)	P_{G1} (MW)	P_{G3} (MW)	P_{G4} (MW)	P_L (MW)
2	93,215.571	99.216	299.611	20.183	1.583
4	84,590.505	91.388	283.516	16.268	1.57
6	111,322.561	114.708	331.364	27.932	1.713
7	145,207.921	140.956	385.077	41.061	2.124
8	154,346.252	147.56	398.523	44.364	2.306
8.5	161,377.042	152.522	408.616	46.846	2.465
9	156,673.062	149.213	401.887	45.191	2.357
9.5	151,277.129	145.345	394.076	43.256	2.186
10	143,467.912	139.7	382.443	40.429	2.017
10.5	133,250.207	132.06	366.826	36.61	1.967
11	129,473.321	129.183	360.897	35.17	1.932
12	118,527.727	120.626	343.25	30.888	1.845
13	115,399.179	118.095	338.103	29.622	1.796
14	116,274.976	118.796	339.566	29.973	1.796
15	115,067.226	117.809	337.576	29.48	1.773
16	116,755.205	119.159	340.396	30.156	1.773
17	122,287.385	123.562	349.453	32.359	1.82
17.5	142,393.989	138.913	380.818	40.038	2.115
18	183,848.594	180.017	420	60.595	2.746
18.5	217,686.873	238.179	420	70	3.01
19	243,833.352	282.314	420	70	3.374
19.5	241,981.121	279.362	420	70	3.38
20	219,244.474	240.974	420	70	3.122
20.5	216,679.09	236.358	420	70	3.142
21	185,327.934	182.175	420	61.669	2.938
22	152,910.221	146.592	396.35	43.877	2.38
23	116,654.701	119.059	340.258	30.107	1.751
24	98,790.598	104.11	309.667	22.631	1.603

The total quantity of CO_2 emitted is shown in Figure 9 and detailed in Table 3, while Figure 10 plots the CO_2 emitted by every power plant.

The results show a difference between the costs of production and the CO_2 emissions. The daily production cost for the WA case is around 4,338,332.219 Nm^3/d and around 4,187,864.128 Nm^3/d for the WAW case, which represents a difference of 150,468.091 Nm^3/d.

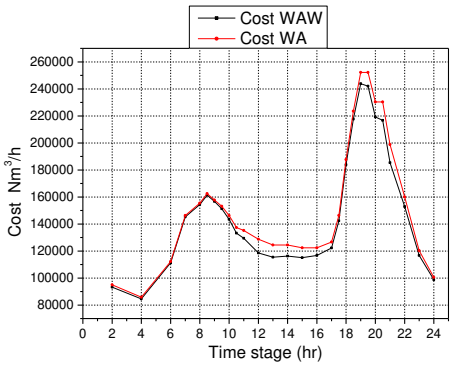

Figure 8
Production Cost

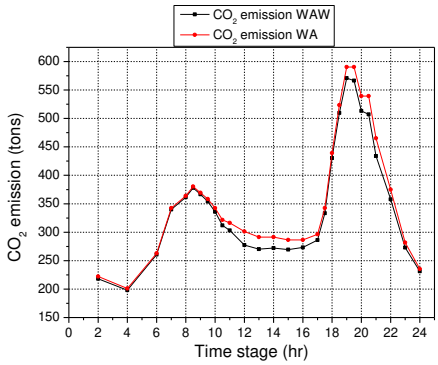

Figure 9
CO_2 Emissions

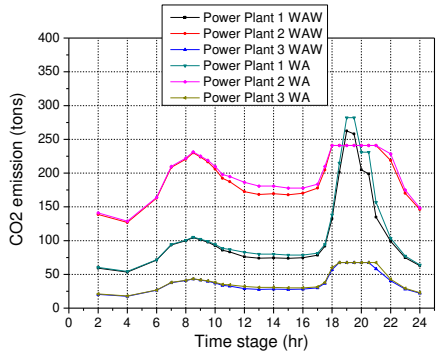

Figure 10
CO_2 emissions by power plants

The daily CO_2 emissions for the WA case are about 10,155.682 tons/d and around 9,803.448 tons/d for the WAW case, which represents a gain of 352.234 tons/d.

This gain is important considering that it is a winter day and therefore not very windy. Assuming that the wind has the same performance during a minimum of 80% of the year, the annual minimum amount of CO_2 the atmosphere that can be saved is of the order of 103,000 tons.

Table 3
Detailed CO_2 emissions

time (hr)	WA-CO_2 (tons)	WAW-CO_2 (tons)
2	222.246	218.210
4	201.075	198.019
6	262.734	260.597
7	342.368	339.920
8	363.831	361.312
8.5	380.343	377.770
9	369.296	366.759
9.5	358.342	354.127
10	342.368	335.847
10.5	321.531	311.928
11	316.419	303.086
12	301.316	277.464
13	291.440	270.140
14	291.440	272.190
15	286.560	269.363
16	286.560	273.314
17	296.359	286.265
17.5	342.368	333.333
18	439.243	430.375
18.5	523.372	509.587
19	590.362	570.794
19.5	590.362	566.458
20	539.279	513.233
20.5	539.279	507.228
21	465.271	433.838
22	374.800	357.950
23	281.718	273.079
24	235.401	231.261

Conclusion

In this paper, we study the effect of the injection of wind farm energy in the western Algerian electrical power system on cost and on the environment.

The dynamic environmental economic dispatch problem is solved via the Harmony Search Algorithm. The HSA is a meta-heuristic that uses a stochastic random search which is simple in concept, few in parameters and easy in implementation. Moreover, it does not require any derivative information.

The simulation results are very conclusive, since we showed that a minimum annual quantity of 103,000 tons of CO_2 emissions can be restricted with a relatively small wind farm. Those emissions are equivalent to the emissions of more than 340,000 average vehicles of which the CO_2 emission factor is equal to 0.2 kg/km [18] and traveling 1,500 km per year.

We recall here that the CO_2 is a gas with notorious greenhouse effect and an average lifespan in the atmosphere of 100 years.

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Heart Rate Variability Monitoring during Human-Computer Interaction

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Abstract: This paper outlines a Heart Rate Variability (HRV)-based method applicable to Human-Computer Interaction (HCI) researches. After a brief overview of various psychophysiology-based empirical techniques (mainly focusing on the mental effort approach), a recent research is shown. The paper presents new results of a short, basic series of experiments, attempting to explore the boundaries of the temporal resolution of the method. The applied INTERFACE methodology is based on the simultaneous assessment of HRV and other data. The results raise hope that this methodology is potentially capable of exploring mechanisms underlying practical usability issues and identifying quality attributes of software elements – over the previously developed HRV-based methods – with a temporal resolution of only a few seconds.

Keywords: Human-Computer Interaction (HCI); software usability testing and evaluation; empirical methods; Heart Rate Variability (HRV)

1 Introduction

To assess the quality of software products, one of the most important keywords is usability. A highlighted usability factor is the mental effort required by current Human-Computer Interaction (HCI). In some definitions of usability as a quality dimension of software products – as it is laid down, e.g., in the original version of the international standard of software product evaluation (ISO/IEC 9126:1991 [1]) – the required mental effort appears not only as a metric, but it is the core of the definition: better quality means that less effort is needed for the usage of the particular software.

Evidently, in addition to subjective methods such as questionnaires, objective methods are also needed to measure mental effort (self-imposed mental work stress).

This paper focuses on the Heart Rate Variability (HRV) power spectrum as a technique for measuring the current mental effort as a function of time. In addition to this, a brief overview of other physiological channels applied to studying HCI is also presented.

This paper presents new results of a foundational research, aiming at exploring the boundaries of the HRV-based method, supporting base data for future applied research, and focusing on future usability evaluations of software.

1.1 Assessing Mental Effort via Analysing Users' HRV Power Spectra

Sometimes the Heart Rate (HR) itself is used in usability evaluations; however, it is not a sensitive measure of mental effort and thus of usability.

The deviation (or variance) of the user's heart rate can give us much better results, but the sources of the variability also include physiological mechanisms independent from the mental effort. Because of this, further spectral analysis of Heart Rate Variability (HRV) is needed. Although in the literature the term "Heart Rate Variability" (HRV) is more frequently mentioned, we prefer the similar expression "Heart Period Variability" (HPV), where the periods of time between consecutive heart beats are simply the reciprocal values of the heart rates: in practice, the periods of heart beats can be analysed more directly, and they can be more expressive.

HRV is applied in various areas. Naturally, there are a series of realizations in medicine (e.g. [14] [17] [18] [19]). Software usability methods have been influenced by these techniques.

The time periods between heart beats are called RR intervals, because they are determined by the highest peaks (the so-called R peaks) of electrocardiogram (ECG) curve. (Additionally, in some papers the RR intervals are referred as the easy-to-remember "Rhythm-to-Rhythm" intervals [29].)

After analysing the variability of the RR intervals, a number of studies [11] [12] [19] [22] [25] [26] [29] [30] [32] [35] have shown that an increase in mental load causes a decrease in the so-called *mid-frequency (MF, 0.07-0.15 Hz) power band* of the Heart Period Variability (HPV) power spectrum. Focusing on this frequency band filters other peaks of the power spectrum: the typical peak in the 0.15-0.45 Hz band corresponds to the respiratory rate (called respiratory sinus arrhythmia); the peak in the 0.04-0.07 Hz band is in connection with the thermoregulatory fluctuations of the blood vessels [12] [19]. Heart rate fluctuations in the MF (0.07-0.15 Hz) power band may also reflect postural changes (via the blood pressure control of the so called baroreflex). To separate the effect of the mental load from the effect of postural changes, a ratio of the MF component around 0.1 Hz and the higher frequency respiratory component can be

applied [30]. However, it is emphasised that if the participants work continuously in a sitting posture (e.g., during computer usage), and their larger muscle movements (e.g., stretching, laughing, sneezing, talking, etc.) eventually are filtered from the records (e.g., via video analysis), the MF (0.07-0.15 Hz) power band itself can characterize the mental effort sensitively enough, as is shown by the following results presented in this paper.

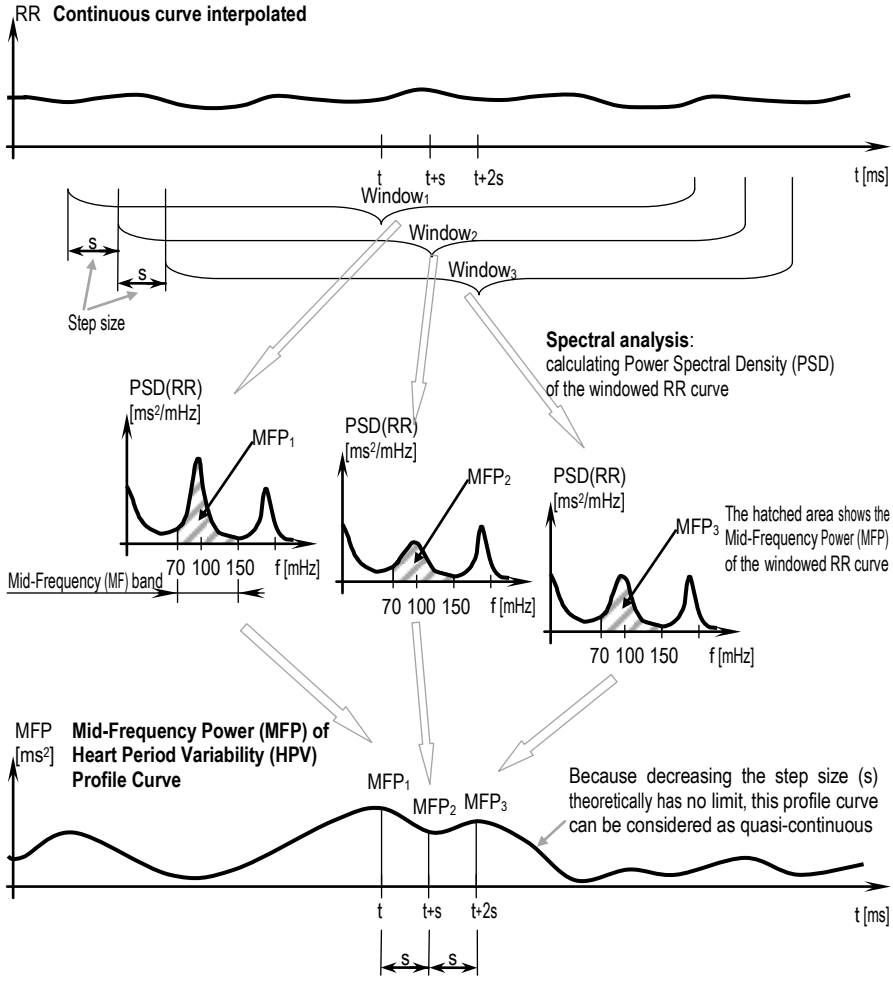

Figure 1

Calculation of the Mind-Frequency (MF) power of the Heart Rate Variability (HPV) profile curve

To assess the spectral components of the HPV power spectra, an integrated system called ISAX (Integrated System for Ambulatory Cardio-respiratory data acquisition and Spectral analysis) was developed and successfully used by Láng

and her team [11] [17] [18] [19]. This equipment and the related method have been integrated into our INTERFACE system.

What we need for practical purposes is the MF power of the HPV power spectrum as a quasi-continuous function of time. If we had such a curve with good-enough temporal resolution, it would be possible to systematically attribute certain salient parts of this curve to observed events of HCI.

To achieve this goal, first let us analyse only one segment at the very beginning of the time series of the RR intervals. This can be performed by applying *windowing* functions: in this way, a selected segment (frame) can be characterized by the calculated MF power of the HPV. When it is done, the frame is shifted a bit further and the spectral analysis is repeated, and so on many times, until the frame reaches the end of the time series (see Figure 1). This kind of analysis technique is embedded in the ISAX system: this windowing technique is applied by scrolling a constant-size frame by small steps (in this series of experiments, 32-second frames were windowed, and the frame was repeatedly shifted by 1-second steps). In this way, the MF power of the HPV power spectrum was automatically calculated for each of the consecutive frames, and it resulted in the desired quasi-continuous time curve, the so-called *MF spectral profile curve*. As the maximal delay of detection is equal to the step size, the change in HPV in principle can be reflected in the spectral profile curve within one second.

The main advantage of our method over the previously developed HPV-based methods [25], in our opinion, is that the MF component of HPV is able to indicate changes in mental effort *within a range of several seconds* (as opposed to the earlier methods with a resolution of tens of seconds at best). This feature was achieved by the following:

- Applying an appropriate windowing data processing technique using the Hamming windowing function to decrease the aperture effect and improve the spectrum image.
- Applying an all-pole auto-regressive model (instead of, e.g., spectrum analysis based on the simple Fourier algorithm) with built-in recursive Akaike's Final Prediction Error criteria [2] [13] and a modified Burg's algorithm [5]. The autoregressive model can already be used in only one cycle, and can give well-established results in the case of 2-3 cycles, contrary to the Fourier algorithm, which requires 8-10 cycles. This means that, if we focus on 0.1 Hz, a 10-second frame can give some results, and a 20- or 30-second frame ensures good result. If the low boundary of the MF band (0.07 Hz) is taken into consideration, a 15-second frame can give some results, and a 30- or 45-second frame ensures good result.
- Creating the above-mentioned spectral profile curve, based on overlapping windows, by finding the best compromise between the spectral and the temporal resolution. A wider window allows for better spectral quality; however, it blurs the effects of longer period.

1.2 Other Physiological Channels Applied to Studying HCI

There exist several other physiology-based techniques to analyse HCI.

A part of these aims to measure actual mental effort, while others aim to identify emotional aspects of HCI. Emotions can represent an independent dimension from the mental effort; however, its importance can also be similarly high in the HCI practice.

Changes in the electrical characteristics of the skin (the so-called Electrodermal Activity – EDA) can be evoked by various physical and emotional stimuli. In our practice, the parameters derived from *Skin Conductance (SC)* responses, especially the Alternating Current (AC) component of the SC, are used.

Although there are other techniques for measuring mental effort and emotions, either they are more difficult to evaluate and more disturbing for the participants (e.g. the Electroencephalograph – EEG), or they give an overall, averaged indicator for a relatively long period of time, from minutes to hours (for example, the visual critical flicker frequency (CFF) and the practical applications of certain bio-chemical measures).

EEG requires sophisticated set of electrodes and the participants experience it as more disturbing. Furthermore, it results in much more complex curves. Various effects have to be filtered from the data, such as the effects of the eye blinks, among many others [3] [23] [35]. Naturally, EEG can explore many more aspects of mental effort than the ECG can; however, if only a single metric of the mental effort is targeted, ECG is a simpler and more preferred method.

Applying EEG can be a potential direction of *further developments* of our methodology: not to simply identify mental effort, but (1) to identify more complex mental or emotional state patterns (using complex methods to analyse the complex curves [4] [21]), or (2) to attempt to localize the active brain regions (using more than 20 [35] or 128- or 256-channel Dense Array EEG (dEEG) [9] [33]).

Electromyography (EMG) measures muscle activity by detecting surface voltages that occur when a muscle is contracted. In isometric conditions (no movement) EMG is closely correlated with muscle tension. When used on the jaw, EMG provides a very good indicator of tension in an individual due to jaw clenching. On the face, EMG has been used to distinguish between positive and negative emotions. EMG activity over the brow (frown muscle) region is lower and EMG activity over the cheek (smile muscle) is higher when emotions are mildly positive, as opposed to mildly negative [24]. Because of the small sizes (the distance between the electrodes is only about 5 mm) and the closeness of the muscles of the different mimic functions, the electrodes have to be positioned extremely carefully [31]. Furthermore, the participants experience the electrodes on the face or head again as more disturbing than the electrodes on the fingers of

the non-dominant hand measuring Skin Conductance (SC). Thus, SC is applied as the simpler and preferred method to identify emotional reactions, instead of the EMG's potential capability of differentiating positive and negative emotions.

Measuring mental effort by visual *Critical Flicker Frequency (CFF)*, and in a biochemical way (measuring, e.g., the *cortisol level of the saliva*) have also been applied by members of our team [12]. However, these methods give only an overall, "washed-together", averaged indicator for a relatively long period of time, from several minutes to hours – this is not the fine temporal resolution targeted by our INTERFACE methodology.

Eye-tracking is a promising direction of *further developments* of our methodology: (1) it is reliably capable of localizing the user interface elements that cause high mental effort or emotional reactions identified by the other physiological channels by synchronizing the channels, and (2) it can be analysed deeper, deriving parameters referring to the state of the nervous system [27].

Pupillometry (measuring the current diameter of the pupil) is a measurement option that is often accomplished with eye-tracker equipment. It is reflective of both the mental effort and the emotions of the user [3] [28] [34]. It can be capable of validating the other physiological channels of our methodology.

Eye-tracking and pupillometry are used in our *ongoing INTERFACE research* [15] [16].

2 Applied Methods

2.1 The INTERFACE Methodology

A complex methodology was developed at the Budapest University of Technology and Economics, by Izsó and his team [6] [7] [8] [10] [11] [12].

Figure 2 shows the conceptual arrangement of the INTERFACE (INTegrated Evaluation and Research Facilities for Assessing Computer-users' Efficiency) workstation.

The advantage of the methodology lies in its capability of recording continuous on-line data characterizing the user's current mental effort derived from *Heart Period Variability (HPV)* simultaneously and synchronized with other characteristics of Human-Computer Interaction (HCI), such as screen captures and a log of all mouse and keyboard use input. In this way, a detailed picture can be obtained which can serve, after a series of careful considerations, as a basis for a deeper understanding and interpretation of the psychological mechanisms underlying HCI.

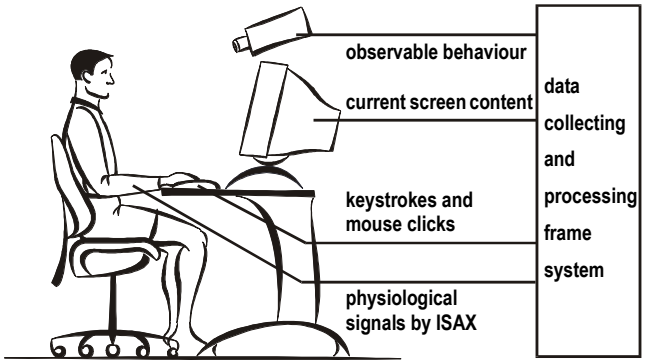

Figure 2
Conceptual arrangement of the INTERFACE software testing workstation

The INTERFACE simultaneously investigates the following:

- Users' observable actions and behaviour
  - keystroke and mouse events;
  - video record of the current screen content;
  - video records of users' behaviour: (1) facial expression, (2) posture and gestures.
- Psychophysiological parameters
  - power spectrum of Heart Period Variability (HPV), regarded as an objective measure of current mental effort – we have applied this measure successfully for more than 15 years [6] [7] [8] [11] [12];
  - in some cases, this system is completed by other physiological channels, such as Skin Conductance (SC) [8], and/or pupillometry and eye-tracking [15] [16] as well.

In addition to observable elements of behaviour, the applied complex method also includes traditional interviews to assess mental models, subjective feelings, and the users' impressions about the perceived task difficulty and the fatigue experienced.

Recording these various data simultaneously requires more technical resources than other empirical methods based on personal observation or simple video recording only. However, the synchronization among multiple channels enables researchers to accurately identify and attempt to interpret significant events during the HCI.

2.2 Experimental Arrangement and Participants

The experiments presented here were carried out at the Budapest University of Technology and Economics.

Three ECG electrodes were placed on the user's torso:

- the exploring (positive) electrode on the 7th or 8th rib (below the left nipple);
- the indifferent (negative) electrode high up on the right side of sternum (breastbone), i.e. on the right side of the manubrium of the sternum, close to the right clavicle (collar-bone), or in the left side of the right infraclavicular fossa;
- the ground electrode on the 8th or 9th rib on the left median auxiliary line.

(Depending on the body form and structure of the participant, other ECG electrode locations can also be selected to maximize the magnitude of the R wave and minimize the artefacts caused by movements).

The signals were recorded by the afore-mentioned ISAX system.

Two notebooks were used: one for the participant, one for the experimenter. Two video cameras (USB web cameras) were applied (one of them with face-tracking capabilities). Instances of the Virtual Dub 1.9 software were applied as video capture software. The video capture of the screen content was realized by the Hypercam 2.1 screen recorder software. The applied keyboard and mouse event logger software, the experimenter's notation software, and the software and hardware elements of the frame system of the synchronization were developed by our team at the Budapest University of Technology and Economics.

For studying the HCI, two pieces of software were used by the participants:

- An arcade game: the 8th episode of the popular YetiSports series (www.yetisports.org), called "Jungle Swing". It had already been applied by colleagues at our department to other experiments [20].
- A game to exercise arithmetic: the Raindrops game of the Lumosity "brain training" web site (www.lumosity.com).

Both games run in web browser – Microsoft Internet Explorer 8 was used. (Because of these circumstances, in this series of experiments, not all the mouse and keyboard events were recorded by our logger software; however, based on the captured screen video, it was possible to reconstruct the mouse and keyboard events).

After three pilot sessions, ten regular sessions were recorded. Seven of the participants of the regular sessions were female, three of them were male. Their ages were 20 to 35.

2.3 The Viewer Screen of the INTERFACE Software

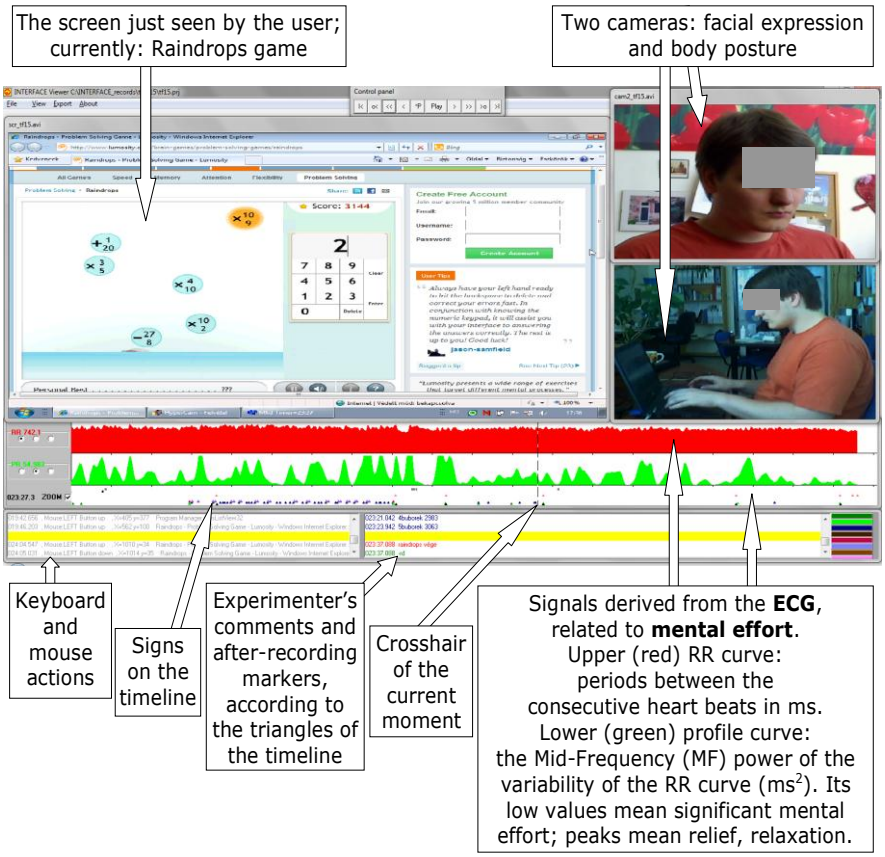

Figure 3

The INTERFACE Viewer screen with a record of the series of experiments. As it can be seen, the user at the selected point is exerting significant mental effort – it is shown by the facial expression and posture of the user and the low value of the last profile curve of the Mid-Frequency (MF) power of the Heart Period Variability (HPV) at the cross-hair. (The curves displayed in the current window show the history of 24 minutes.)

The most important strength of the INTERFACE Viewer software is its ability to synchronize and play the records of the different data channels strictly simultaneously. Figure 3 shows the INTERFACE Viewer screen with a record of the current series of experiments. This figure also shows the typical pattern of mental effort observable both on the HPV curve and in the video images.

2.4 Schedule of Each Session

Each session had the following schedule:

I At the beginning of each session, we performed a "calibration" phase

1 First, the participant was asked to *relax* for approximately two minutes. The instructions of the relaxation periods were always the same:

- seating themselves in a comfortable posture, without any movement,
- keeping their eyes open,
- trying to be thinking of nothing, in spite of our knowing it is not trivial for people untrained to this (at least trying to avoid to think specific items),
- calming them down, ensuring them that there are not good and bad personal results: we have no expectations, we would like to experience only some differences between this period and the next one.

2 The relaxation was followed by a two-minute artificially induced high mental effort exercise: mental arithmetic. However, after the instructions, an *anticipation* period (20 seconds) followed: forcing the participant to wait for the next, mental effort demanding task. Both the anticipation and the mental arithmetic task were controlled by a PowerPoint slide show. The preliminary instructions of the *mental arithmetic* periods were also always consequent:

- no movements,
- no speech, no aloud counting, and neither voiceless movement of mouth,
- after giving the participants a starting number by the slide show (in these cases: 11558), the participants immediately had to count backwards by 7s (it is really difficult and requires a high level of mental effort);
- two minutes later, the result of the counting was asked by the slide show – however, the actual result of the counting was not really important in itself; the only goal was to artificially generate mental effort.

  It was an important element of the experiment design that the mental arithmetic periods were immediately followed by *relief* periods: after answering the result of the mental effort demanding task, there came 10-20-second periods without anything to do (without new instructions, but only with some confirming smile).

II Playing with the mentioned *YetiSports computer game*

This game was selected because of the simplicity of the interaction: the user has to use only one mouse button and just click at the right time. In this 8th episode called Jungle Swing, the yeti hangs and swings around branches of trees. By pressing the mouse button, the all-the-time-swinging yeti swings away from the branch tangentially. The goal of the game is to help the yeti to get to the highest branches of a tree. To do so, one must figure out the best timing for the yeti; when to leave the branch to jump to the next branch where it starts to swing around the new branch, and from where it can jump further and further again [20].

If the user (player) fails to do so, the yeti will fall down, until it is able to catch a branch or until it falls into the water underneath. After falling down into the water, a message box appears; then when the player clicks the button, the start screens of the game are displayed. It means that each fall into the water is followed by the same five clicks to restart the game, and to make a new attempt. This alternation of concentration-requiring attempts and drilled, easy clickstreams to restart the game has a role in this series of experiences.

The game looks easy; however it is very hard for anyone who is a novice. The jumps are difficult to make; they need very precise timing. To avoid severe frustration that could influence the subsequent tests, we ended the game at the first instance of the participant making at least four successful jumps in a row.

III Playing with the mentioned *Raindrops arithmetic exercise game*

This game is an arithmetic test, where participants have to solve short equations, such as 4+9, or 16/4, within a given time period. Each equation appears in a raindrop, falling towards the bottom of the screen, and has to be solved before it reaches the ground or the water level rises. If the water level reaches the top of the screen, the game ends. The equations become more and more difficult (additions and subtractions at first, then multiplications and divisions later), and over time they become more frequent.

2.5 HRV Analysis, Statistical Analysis

Data recording of the ECG peaks was performed by the ISAX equipment, as was mentioned in the introduction. Data processing of the collected raw ECG peaks and the power spectrum analysis were performed by the ISAX software. Creating the mentioned spectral profile curve, the following parameters were applied:

- frequency band: 0.07-0.15 Hz (MF);
- size of the windowing frame: 32 sec;
- steps (shifts) of the windowing frame: 1 sec.

Because of the low number of participants, the normality of the distribution of measured parameters cannot be proved. Therefore a non-parametric statistical method, the Wilcoxon Signed Ranks Test, was used to test the differences.

Statistical analyses were performed using the IBM SPSS Statistics, version 19.0.

3 Results

3.1 Differences between the Mental Effort Values Measured during the Different Tasks

The curves shown in the Figure 4 were recorded during the 6th session.

In Figure 4 the upper (red) curve represents the RR values (heart periods), and the bottom (green) one displays the Mid-Frequency (MF) power profile curve of Heart Period Variability (HPV).

During relaxation, the MF component of the HPV increases, so the profile curve runs relatively high (and, naturally, the RR curve has zigzags). In the case of "perfect" relaxation, the profile curve should be continuously high. However, this is not expected in this experimental situation: the participants were not trained to use advanced relaxation techniques.

Then the anticipation section follows.

During the mental arithmetic exercise, the RR curve definitely gets smoother, and consequently the profile curve also gets significantly lower. In this figure, the profile curve can be considered low, especially in comparison with the other sections.

After the "calibration" tasks, the participants are relieved.

In Figure 4, the curves show that this participant really could relax. (The profile curve in Figure 4 has its highest peak in the middle of the section of relaxation.) However, in this series of experiments, most of the participants could not relax well: they were just wired, and they felt the relaxation as a serious task, and it even caused a certain task load. However, the mental arithmetic exercise usually results in the excepted low curve, which can be used as a baseline. Furthermore, in most cases, during the mentioned short period of relief, the participants get more relaxed than during the conscious, intended relaxation: the MF of HPV profile curves have their highest peaks here (this is the so called "rebound" phenomenon). And, in most cases, the anticipation period meant more relaxed phases than the original relaxation task.

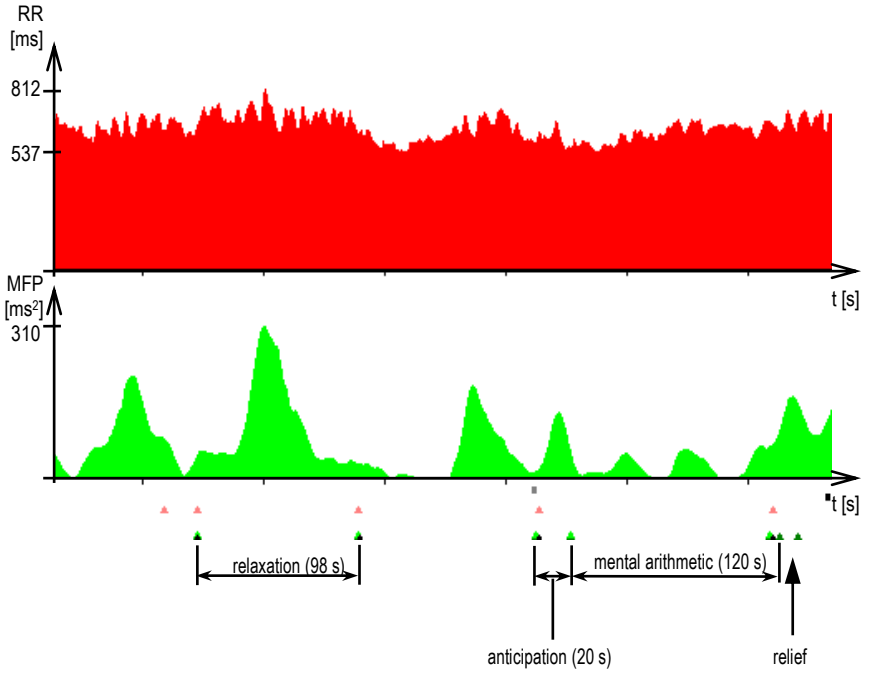

Figure 4

The typical pattern of the relaxation and mental arithmetic periods in the case of the 6th participant. The expressive visualisation style of the INTERFACE Viewer software is applied. The upper (red) curve represents the RR intervals (heart periods), and the bottom (green) one displays the Mid-Frequency (MF) power profile curve of the Heart Period Variability (HPV).

Figure 5 compares the values of the MF power of the HPV profile curves during the above mentioned "calibration" phase and the playing phases.

Studying the results of the ten sessions, the MF power of the HPV profile curve values looks higher during the relaxation periods than during mental arithmetic. However, the Wilcoxon Signed Ranks Test has not proven the difference (sig. 0.254>>0.05). It may be caused by the mentioned effects (or, naturally, it was influenced by other effects). Probably a sample of a higher number of participants could give significant result also with these circumstances.

However, the differences between the mental arithmetic task and the anticipation period, and the mental arithmetic task and the relief are significant: the Wilcoxon test results *sig. 0.019* and ***sig. 0.005***.

In Figure 5 the YetiSports looks easier than the Raindrops, and the Raindrops looks easier than the pure mental arithmetic test of the "calibration" phase. However, these differences are not significant in term of statistics. In comparison of the two games, the Wilcoxon test results sig. 0.069>0.05.

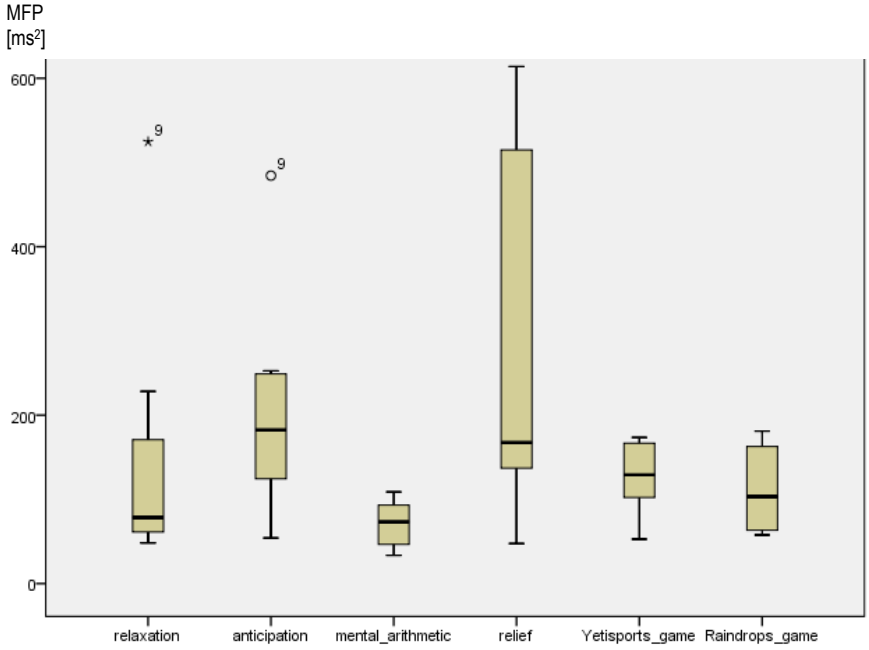

Figure 5
Boxplots[1] of the Mid-Frequency (MF) power of Heart Period Variability (HPV) values during the different tasks and periods

3.2 A Highlighted Result of the Current Series of Experiments: Proofing the Differences between Short Periods

As was mentioned earlier, the YetiSports game is very difficult. During the 5-15 minutes of play with this game, each player had 11-35 attempts. It means that most of the attempts were really short; a number of them contained only a single jump (of course, an unsuccessful jump, and a fall). Other, rare attempts contained 5-10 jumps. The average length of an attempt is 16.4 sec (min. 4.5, max. 79.4, std. dev.: 11.0).

[1] Boxplots are applied as usual. The dark lines in the middle of boxes are the medians. The bottoms of the boxes indicate the first quartiles, the tops of the boxes represent the 3rd quartiles. The T-bars (the inner fences or whiskers) extend to 1.5 times the height of the box, or, if no case/row has a value in that range, to the minimum or maximum values. The circles and asterisks are outliers – these are defined as values that do not fall in the inner fences. Asterisks are extreme outliers – these represent cases/rows that have values more than three times the height of the boxes.

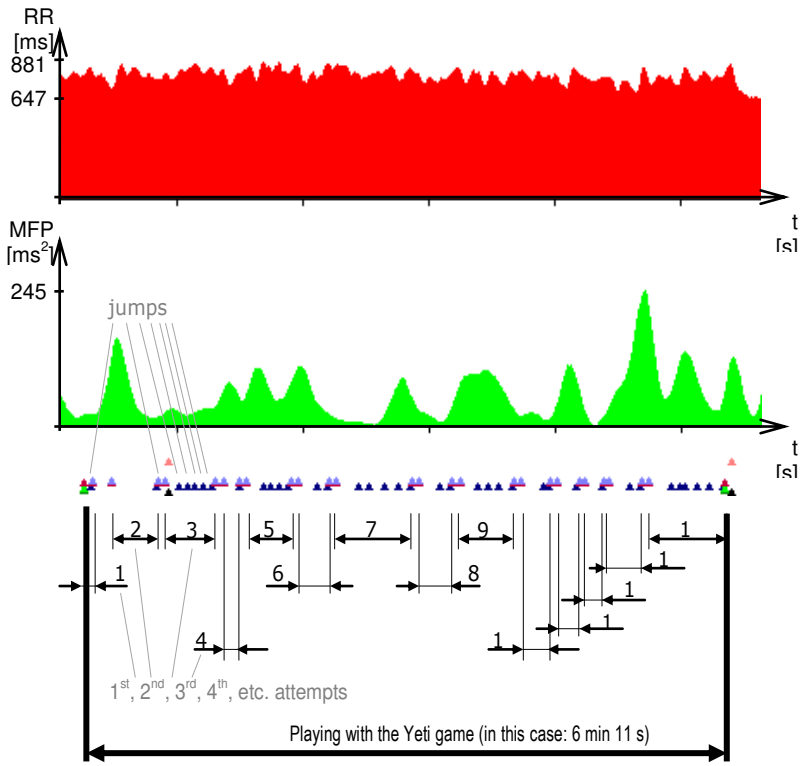

Figure 6

The typical pattern of the playing with the YetiSports arcade game in the case of the 10th participant. The upper (red) curve represents again the RR values (heart periods), and the bottom (green) one displays the Mid-Frequency (MF) power profile curve of the Heart Period Variability (HPV). In this case, during the play, the user had 14 attempts. Some of the attempts meant only one jump, and the yeti immediately fell down (during the 1st, 2nd, 4th, 11th attempts). Some of the attempts were more successful (e.g. the 3rd attempt contained 5 jumps, the 14th attempt contained 6 jumps). The periods between two attempts are short (in this case the average was 4.7 sec, the shortest one was 3.2 sec). As it can be seen, these periods (simply clicking 5 times after each fall down to restart the game) usually do not show mental effort: most of them are followed by peaks of the profile curve.

As was mentioned earlier, after each fall down, 5 clicks are required to restart the game. These are simple, effortless clicks, each time using the same buttons. These periods between two consecutive attempts are short. The average length of a "break-time" between two consecutive attempts is ***6.2 sec*** (min. 3.2, max. 13.9, std. dev.: 2.4).

The typical pattern of alternation of these two types of periods are shown in Figure 6.

The alternation of the MF power of HPV is significant, ***in spite of the very short periods***!

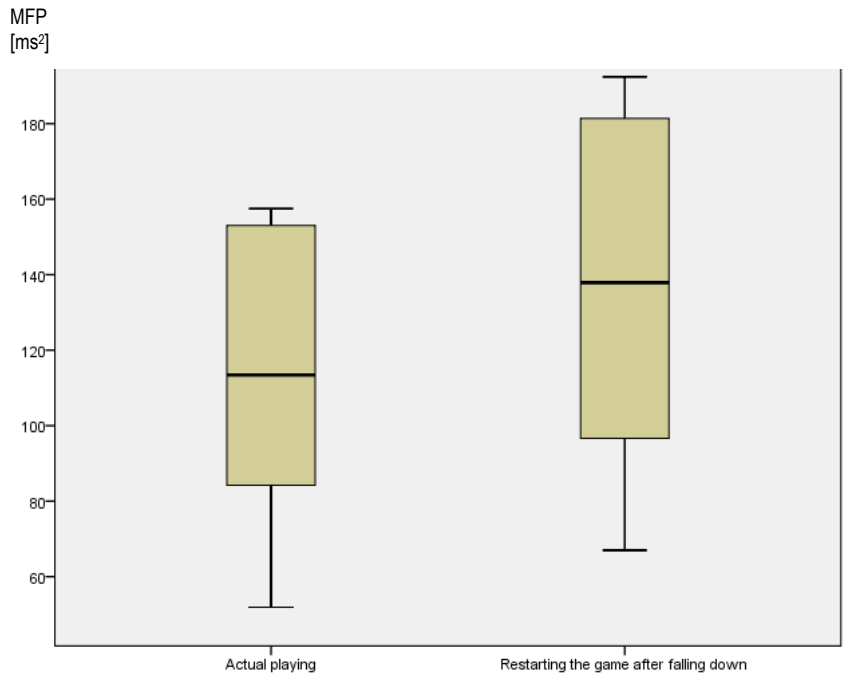

Figure 7

Comparing the mental effort required by the attempts of playing with the YetiSports arcade game (actual playing) and the easier "breaking-time" periods between the consecutive attempts (simply clicking 5 times after each fall to restart the game). (These periods are exactly defined in the main text.) The boxplots[1] show the significant difference (*sig. 0.006*) between the aggregated Mid-Frequency (MF) power of Heart Period Variability (HPV) values during these periods.

The comparison of the aggregated values of the "actual playing" periods and the "breaking-time" periods is shown in Figure 7. The definitions of these periods were the following:

- Actual playing period = from last click on the button right before the appearance of the yeti until the disappearance of the falling yeti.
- Breaking-time period = from the disappearance of the falling yeti until the last click on the button right before the next appearance of the yeti.

The Wilcoxon Signed Ranks Test has proven the difference: ***sig. 0.006*** << 0.05.

Discussion

Based on the results presented here as well as in other related papers, it can be stated that the INTERFACE methodology already in its present form is capable of identifying the relatively weak points of the HCI. With this methodology, it was possible to study events occurring during the HCI *in such a high temporal resolution* and with such objectivity that would not have been possible using other

methods presently known to us. (An overview of other methods was presented in the Introduction.)

The applied Heart Period Variability (HPV) profile function integrated into the INTERFACE system seems to be a potentially powerful tool for monitoring events in very narrow time frames. The theoretical establishment of this feature was explained in section 1.1, and the results of this series of experiments have empirically proved the capability of identifying differences of 6.2 sec periods).

Naturally, analysis of the synchronized records of physiological data and videos together is a must. By the help of the video records of the cameras, for example, the artefacts of HPV caused by large muscle movements (such as stretching) can be filtered out; these peaks of the profile curve cannot be interpreted mechanically as decrease of mental effort. In other cases, the peaks of the profile curve can indicate relaxed periods during easy software-usage, or they can indicate "giving up" ("no coping any more") situations; they can be differentiated on the basis of the efficiency of the activity of the participant. (Even if there are objective performance metrics, however, this interpretation must be carried out very carefully.)

After appropriate artefact filtering, decreases in the MF spectral profile may indicate periods requiring mental effort during the HCI – however, these can be caused not only by usability problems of the software (software flaw). Mental effort can also be attributed to the imperfection of the training of the user (user error), or it can be caused by normal accompanying effort (e.g., naturally, mental effort is required in learning tasks when using e-learning software or accomplishing creative tasks), or sometimes it can also be caused by other thinking process of the participant, independent from the actual software use. The interpretation must be based on exploring the recorded keyboard and mouse event logs and the captured screens. It can also be helped by interviews. However, understanding the real mechanisms underlying the interactions still remains difficult.

The results presented in this paper show new possibilities that can be applied in future assessments of HCI. The diagnostic value of these new possibilities may be explored during future studies. Naturally, further validation and exploration of the boundaries of the possibilities are also needed.

Involving more channels is a possible way to improve this methodology. If different channels indicate the same attributes (e.g. if the HPV profile curve shows a decrease, the video images of the posture, gestures, and facial expression show mental effort, and the person himself confirms it during the interview), the synergy between them can help in forming interpretations.

In other cases, the different channels can complete each other. For example, measuring the Skin Conductance (SC) and/or pupil size are a new opportunities to modulate the results. These new opportunities can initialize new studies.

Acknowledgement

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