APPLIED COMPUTER SCIENCE

The Journal is a peer-reviewed, international, multidisciplinary journal covering a broad spectrum of topics of computer application in production engineering, technology, management and economy.

The main purpose of Applied Computer Science is to publish the results of cutting-edge research advancing the concepts, theories and implementation of novel solutions in computer technology. Papers presenting original research results related to applications of computer technology in production engineering, management, economy and technology are welcomed.

We welcome original papers written in English. The Journal also publishes technical briefs, discussions of previously published papers, book reviews, and editorials. Especially we welcome papers which deals with the problem of computer applications in such areas as:

- manufacturing,
- engineering,
- technology,
- designing,
- organization,
- management,
- economics,
- innovations,
- competitiveness,
- quality and costs.

The Journal is published quarterly and is indexed in: BazTech, Cabell's Directory, CNKI Scholar (China National Knowledge Infrastucture), ERIH PLUS, Index Copernicus, J-Gate, Google Scholar, TEMA Technik und Management.

Letters to the Editor-in-Chief or Editorial Secretary are highly encouraged.

CONTENTS

Applied Computer Science, vol. 15, no. 1, pp. 5–17
doi:10.23743/acs-2019-01

Submitted: 2018-12-07
Revised: 2019-02-04
Accepted: 2018-03-18

design patterns, software quality, quality assessment

Rafał WOJSZCZYK [0000-0003-4305-7253]*

VERIFICATION OF ACCURACY AND COST OF USE METHODS OF QUALITY ASSESSMENT OF IMPLEMENTATION OF DESIGN PATTERNS

Abstract

Professional programmers use many additional tools over the Integrated Development Environment during their work. Very often they are looking for new solutions, while expecting that the new tool will provide accurate results, and the cost of use will fit within the planned budget. The aim of the article is to present the results of two comparative analyzes carried out in terms of accuracy and the cost of using the quality assessment method of implementation of design patterns.

1. INTRODUCTION

A programmer is a unique craftsman because the products he produces are made using tools created by other programmers or sometimes by himself. This allows programmers to create new, unique solutions, often non-standardized. Ultimately, this leads to the creation of new tools that support the work of programmers. Examples of such solutions are design patterns. Patterns from (Gamma, Helm, Johnson & Vlissides, 1994) have been known for many years, although these are still the same patterns that their implementation is constantly changing.

A programmer implementing design patterns does so on the sample templates from (Gamma, Helm, Johnson & Vlissides, 1994; Metsker, S. J., 2004) and his own knowledge, during which he usually focuses on achieving the purpose

* Koszalin University of Technology, Department of Computer Science and Management, Śniadeckich 2, 75-453 Koszalin, Poland, rafal.wojszczyk@tu.koszalin.pl

of the pattern (solving the programming problem). The implementation of the pattern goal in accordance with the template from (Gamma, Helm, Johnson & Vlissides, 1994) does not mean a beneficial implementation, because each computer program is different. The preferred implementation of the template is a fragment of the source code that meets additional expectations, otherwise it provides benefits in selected criteria. Assuming the low development and integration cost criterion, this means that the template code will not require additional modi-fications when expanding and integrating with this code. Therefore the cost of the development will consist of the cost of adding new parts of the code that use existing pattern implementation. In this context, a programmer working in an agile team after doing his job (writing the source code, usually without complete documentation) is looking for the answer to the question: *will the implement-tation of a given design pattern provide the benefits expected from this pattern?* The method that supports the answer to this question should be accurate and at the same time cheap to use. Well-known software quality models are too imprecise for this purpose, or generally do not take into account design patterns. However, the methods analyzing the implementation of design patterns are often too expensive to use (especially in Agile teams, where the amount of documentation is limited). The aim of the article is to present the results of the verification of the method, which allows the answer to the above question, and at the same time meets the imposed restrictions on accuracy and cost.

The second chapter explains what the quality of pattern implementation is and presents selected related works. The third chapter contains comparative analyzes and results. Fourth chapter shows the results of the use of the method in the production environment, it means practical use. The last chapter is a summary of the article.

2. QUALITY OF IMPLEMENTATION OF DESIGN PATTERNS AND ALTERNATIVE METHODS

2.1. Quality of pattern implementation

The criteria of the assessment of quality in terms of the cost of development and software integration are one of the most important for the vendor. The vendor, who constantly keeps and develops his product, even for many years, should take care of the fact that the cost of running and development are as low as possible. For that purpose design patterns are used. It has been widely accepted, that programmers are implementing patterns on the second level of quality, i.e. so that the implementation meets only the presented aim of the pattern, e.g. one instance of the object in the Singleton pattern. First level of implementation quality is undesirable, such an implementation contains errors, e.g. the public constructor of the class of Singleton pattern. Both 1st and 2nd level of implementation quality

does not provide the benefits that were explained in the introduction, this is only ensured by implementation on the third level of quality. Level 0^{th} is a special case when there is no fragment in the code that matches the pattern. A comparison of all quality levels is shown in fig.1. Leaving the implementation on the 1^{st} and the 2^{nd} level in the production software will cause additional costs in the future.

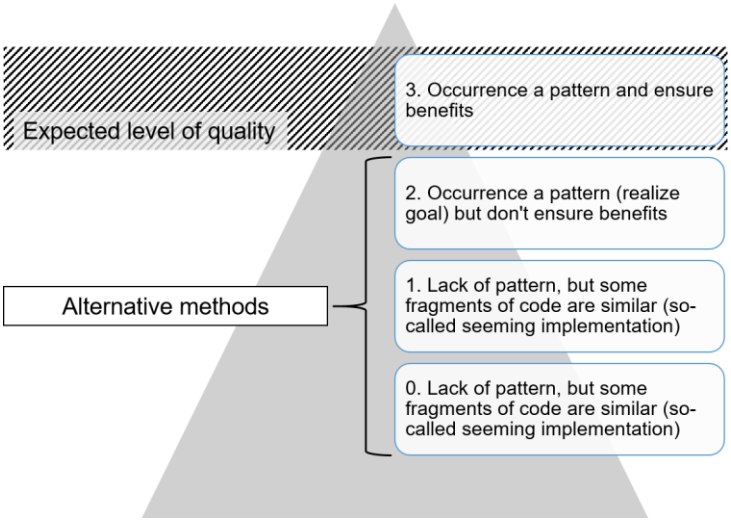


Fig. 1. A comparison of the levels of implementation of design patterns quality

2.2. Alternative methods

The quality of the source code is commonly associated with object-oriented software metrics. Unfortunately, popular metrics do not apply to the implementtation of design patterns, despite the cost of use acceptable in agile vendor teams. Amongst the scientific research related to this issue, the dominating problem is the search for occurrence design patterns (Singh Rao & Gupta, 2013; Tsantalis, Chatzigeorgiou, Stephanides & Halkidis, 2006). The result of the method of finding the occurrence is the number of occurrences of patterns in examined part of the program code or the equivalent of the code. One occurrence of the pattern in most methods is only an information about a compatibility of a part of the code with the template describing reference pattern, on the basis of this part of the code is classified as the occurrence of the pattern. Most methods searching for an occurrence of patterns works in binary, i.e. indicates an occurrence of the pattern or no pattern, which corresponds to an estimation of the assessment of 2^{nd} or 0^{th} level of the quality of implementation, despite all this is insufficient accuracy. Chosen methods additionally enable to show an incomplete occurrence of the pattern (e.g. it contains errors or deficiency in implementation), which corresponds to 1^{st} level of implementation quality. The cost of using methods

searching for occurrence of the patterns is in most cases accepted agile vendor teams. Other research concern methods of verification of pattern implementations, which once again rely on showing the compliance of the tested part of the code with design pattern template (Mehlitz & Penix, 2003; Nicholson et al., 2014). The result of the implementation verification method is the indication of a part of the code, that is compatible with the pattern template. Full compliance with the template corresponds to the 2nd level of quality of implementation, while the exceptions from this correspond to 1st and 0th level. Cost of using methods verifying the implementation of patterns is bigger than possibilities of the agile team, since detailed documentation is required. To sum up, alternative methods do not allow to distinguish implementation compatible with the 3rd level from the 2nd level of quality, i.e. it is not possible to assess whether the implementation of a given pattern provides the expected benefits, including lower costs of development and integration.

3. COMPARATIVE ANALYZES

3.1. Accuracy

Most of the alternative methods are designed to detect instances of design patterns, in addition, these methods are limited to the most popular implementations of patterns that only provide the goal, i.e. the 2nd level of implementation quality. Direct comparison of the proposed method with methods of searching occurrences is unreliable because the result of the search methods (number of occurrences of a given pattern) does not contain information on the quality of implementation of these instances.

In addition to the destination, alternative methods differ in application to selected programming languages. Most alternative methods use Java, and in the case of Danyko the basic language is C#. Despite the many similarities of these languages, this is another reason for direct comparison.

Having considered the above-mentioned difficulties in conducting a direct comparison, methods of similar purpose were selected: (Blewitt, 2006; Nicholson et al., 2014; Mehlitz & Penix, 2003). Then, on the basis of a common representation, a comparative analysis of these methods was carried out, the aim of which is to demonstrate greater accuracy in the analyzed properties of design patterns (which is necessary to distinguish between level 2nd and level 3rd of the implementation quality).

The comparative analysis was performed by decomposing the properties of design patterns, which are analyzed by methods. The Singleton (Wojszczyk & Khadzhynov, 2017) and Strategy (Wojszczyk, 2018) patterns have been limited to an exhaustive example. Each property broken down by the methods compared is assigned the appropriate point value:

- 0 – the method prevents the measurement of a given property of the pattern,
- 0.5 – the method measures ownership inaccurately or does not include all elements in a given property,
- 0.7 – the specification of the method allows to measure a given property, but the author of a given method did not include it in the application to a given pattern,
- 1 – the method measures a given property without reservation.

The result of the comparative analysis is presented in Tables 1–2. Values were introduced after the analysis of each method, using the specification of standards in (Blewitt, 2006), instruction manual up to (Nicholson et al., 2014). The result of the comparative analysis is presented in Tables 1–2. Values were introduced after the analysis of each method, using the specification of standards in (Blewitt, 2006), instruction manual up to (Nicholson et al., 2014). The Strategy template is not described in the specification (Blewitt, 2006), which does not mean that it is not possible to verify the implementation of this pattern. The values in Table 2 are entered on the basis of other standards described in (Blewitt, 2006).

After analyzing the results presented in Tables 1–2, it can be noticed that accuracy in alternative methods is underestimated by fine grained properties, i.e. occurring at the level of individual lines of code. This type of property can be measured with typical numerical metrics (eg, the AHF metric from the MOOD set measures the encapsulation of fields). Next factor reducing the accuracy of alternative methods is the lack of other modifiers and access modifiers. In a case where exactly one of the modifier is expected, it is obvious. However, in other cases, when other modifiers are allowed, this limits accuracy. In the case of (Blewitt, 2006), the lower accuracy is caused by the lack of alternative properties, i.e. only those defined in (Nicholson et al., 2014) are allowed and the others are unacceptable, although they do not constitute inferior solutions.

Tab. 1. Result of the benchmarking for the Singleton pattern (instance sharing by the field), method A – (Blewitt, 2006), method B – (Nicholson et al., 2014), method C – (Mehlitz & Penix, 2003)

Category	Element	Occurrence	Danyko	Method A	Method B	Method C
Field	Modifier	static	1	1	1	0
		default	1	0.7	0	1
		others	1	0.7	0	0
	Access Modifier	public	1	1	1	0
		default	1	0.7	0	1
		others	1	0.7	0	0
	Name	contain „Singleton”	1	0	0.5	0.5
Type	Kind of Type	class	1	1	1	1
		others	1	0.7	0	0
	Modifier	abstract	1	1	1	0
		default	1	0.7	0	0.5
	Access Modifier	public	1	1	1	0
		default	1	0.7	0	1
Constructor	Modifier	default	1	1	1	1
		others	1	0.7	0	0
	Access Modifier	private	1	1	1	0
		others	1	0.7	0	0
Initialization	Checking the existence of an object		1	1	0	1
	Initialization on first use		1	1	0	1
Multi-threading	Synchronization of access to instances		0.5	1	0	1
Use by other types	Kind of relation	association	1	0	1	1
		Inheritance	1	0.7	1	1
	Number of uses		1	0	0	0
Content of Singleton class	The number of methods / fields / properties		1	0.5	0.5	0
	Encapsulation of fields		1	0.5	0.5	0
	detection of additional static elements		1	1	1	0
		Total	**25.5**	**19**	**11.5**	**11**

Tab. 2. The result of the comparative analysis for the Strategy pattern, method A – (Blewitt, 2006), method B – (Nicholson et al., 2014), method C – (Mehlitz & Penix, 2003)

Category	Element	Occurrence	Danyko	Method A	Method B	Method C
Interface declaration	Modifier	default	1	1	1	1
		others	1	0.7	0	0
	Access Modifier	public	1	1	1	0
		default	1	0.7	0	1
		others	1	0.7	0	0
	Name	contain „Strategy”	1	0	0.5	0
	Kind of type	Interface	1	1	1	0
		class	1	0.7	0	1
		others	1	0.7	0	0
Operation declaration	Modifier	abstract	1	1	1	0
		default	1	0.7	0	1
		others	1	0.7	0	0
	Access Modifier	default	1	1	1	1
		others	1	0.7	0	0
	Number of operation		1	0.5	0	0
Implementation of the interface	Modifier	abstract	1	1	1	0
		default	1	0.7	0	1
		others	1	0.7	0	0
	Access Modifier	default	1	1	1	1
		others	1	0.7	0	0
	Kind of type	class	1	1	1	1
		others	1	0.7	0	0
	Implementation of the interface		1	0.5	1	0
	Number of operation		1	0	0	0
Choice of strategy	Number of called strategies		1	0	0	0
Total			**25**	**17.4**	**9.5**	**8**

3.2. The cost of use

When choosing the methods for comparison in terms of the cost of use, it was limited to the methods selected in the previous section, excluding the method (Mehlitz & Penix, 2003) due to the lack of sufficient information about the costs of using this method.

The cost of using the method can be divided into two types: one-off costs initially incurred, before the first use of the method and recurring costs each time the method is used. One-off costs are the construction of templates for design patterns, which should be preceded by assimilation of the appropriate formal representation. The comparison made is limited to individual costs, i.e. one pattern template, one use of the method. The recurring costs include:

- obtaining software or converting source code to a formal form,
- performance of the quality assessment process (or verification of implementation in the case of alternative methods),
- extension of the pattern template with a new variant,
- adding a new assessment criterion,
- obtaining information about changes to improve implementation.

The proposed method and (Blewitt, 2006) include both of these types of costs. However, in (Nicholson et al., 2014) it is necessary to create the appropriate documentation every time, which means that it cannot be considered a one-time cost.

Man-hours are the most authoritative unit that can be used to express the cost of using the method. Unfortunately, the comparison of methods based on such a unit of measure may be biased, because it significantly affects this experience with a given method. An alternative unit of measure may be the number of data entered into the methods, e.g. number of words, operations performed, etc. The number of data entered may be influenced by many factors that are not directly related to the method, e.g. interfaces for communication with the operator, developed tools. Defects resulting from imperfections of interfaces and tools should not affect the cost of using the method. After taking into account these shortcomings, a proposed unit cost per use 1us was proposed – one imaginate Singleton, which corresponds to the workload needed to define a template for a Singleton design pattern in a given formal representation. There is a finite number of elements describing this pattern with each template of the pattern, so with such a defined unit 1us corresponds to 16 elements in the Danyko method, 12 in (Blewitt, 2006) and 8 in (Nicholson et al., 2014). In simplified terms: let Singleton (static field) consist of 3 elements (class, constructor, field) then the work needed to build a template of this pattern equals 1us. Then Singleton enriched with a property (meaning one more element), will be equal to 1⅓ us. In the case when the method prevents the execution of a process related to a given cost component (eg. it does not provide information on possible changes in the implementation), 1us is assigned. Table 3 presents the result of the comparative analysis carried out in terms of the cost of using the methods.

The cost analysis presented in Table 3 does not reflect the production cost of use, i.e. the addition of a new variant is performed once per several iterations, as opposed to the evaluation that is performed cyclically in each iteration. The production cost of using the methods was calculated by simulation, which is based on information received from the external team of the programming company.

The employees estimated that during one year of work they would have incurred the following costs of the method (for one pattern): 1x learning the formalization method, 1x building the pattern, 30x obtaining the code and also the cost of performing the assessment, 15x getting a suggestion for improvement, 3x adding a new variant, 1x adding a new assessment criterion. The sum of individual costs and the sum of simulations are presented in Table 4.

Tab. 3. Comparative analysis of the cost of using particular methods

The type of cost	Danyko	(Blewitt, 2006)	(Nicholson et al., 2014)	Comments
Learning how to formalize	1	1	3	Cost estimated by a team of an external software company
Construction of the reference Singleton	1	1	1	The reference cost from which the unit 1us results
Acquiring the source code	0.1	0.1	0.5	In Danyko and (Blewitt, 2006) it is automated
Performing the assessment or verification	0.1	0.1	0.1	Each method is able to automate this process
Addition of a new variant	0.3	1	1	In the case of (Blewitt, 2006) and (Nicholson et al., 2014) this is not possible, it is necessary to replicate the whole pattern
Addition of a new assessment criterion	0.3	1	1	
Getting suggestions for improvement	0.1	1	0.1	In case of (Blewitt, 2006) this is not possible, in the others it requires reading from the template pattern

Tab. 4. The result of the cost comparison of methods

	Danyko	(Blewitt, 2006)	(Nicholson et al., 2014)
The sum of individual costs from table 3	2.9	5.3	6.7
Sum of costs from simulation	10.7	27	27.5

The high costs of using alternative methods that resulted from the simulation occur mainly in repeatedly performed single costs, such as acquiring source code or obtaining suggestions for improvement. This underlines the important role of adequate formal representation, which confirms the thesis about the choice of data structures based on the object-oriented programming paradigm.

4. PRACTICAL VERIFICATION

Verification of the method carried out in cooperation with the company Poland, which provided the source code. Experiment was carried out using the Command and Factory patterns, which belong to one of the most popular patterns.

The aim of the Command pattern is (Gamma, Helm, Johnson & Vlissides, 1994): *encapsulation of requests in the form of an object*. This allows the client to be parameterized using different requests, and putting requests in queues and logs, as well as provide and undo operation support. Implementation of the pattern is useful when many different operations can be performed on one object (e.g. a bank account). Figure 2 shows a class diagram with an example pattern implementtation, on the basis of (Gamma, Helm, Johnson & Vlissides, 1994). The diagram from the figure 2 shows a structural variant, the modification of this variant is a variant with dynamic mapping (connections in Client class are created dynamically, e.g. by reflection mechanism or injection of dependencies). Presented implementation meets 3rd level of quality.

Elements, of which the Command pattern is made of (Gamma, Helm, Johnson & Vlissides, 1994):

- *AbstractCommand* class – declares a common point to perform operations, other names: parent class, parent type, general command,
- ConcreteCommand – includes the implementation of the *Execute* operation in the form of calling appropriate operation of the Receiver object, other names: Concrete command, subclass,
- *Receiver* – executes a specific command (algorithm), other names: recipient,
- *Client* – creates objects of specific commands and determines connections (maps) with recipients, other names: map, connection mapping,
- *Invoker* – request servicing of the command, other names: sender.

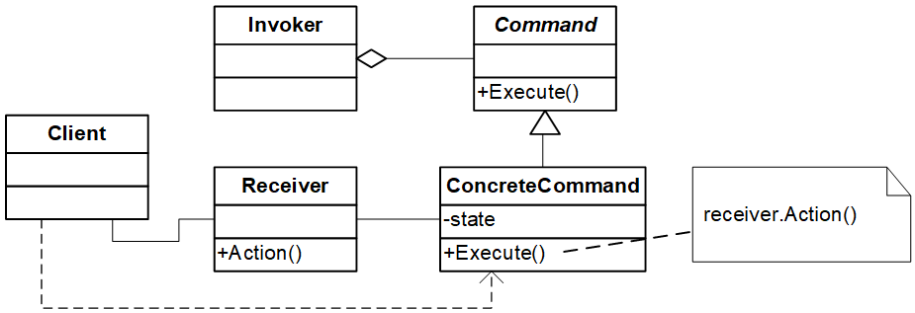


Fig. 2. Class diagram of command pattern, UML notation

The purpose of the Factory pattern is (Gamma, Helm, Johnson & Vlissides, 1994) *to define the interface for creating objects, while the act allows subclasses to determine the class of a given object the creation process is passed to the subclasses*. The implementation of the pattern is useful when different objects carrying information can be created from one operation. Figure 3 shows the class diagram of the sample implementation pattern, on the basis of (Gamma, Helm, Johnson & Vlissides, 1994) and (Metsker, 2004). In (Gamma, Helm, Johnson & Vlissides, 1994) Factory patterns, i.e. Abstract Factory and Factory Method

are described separately, although they are included in one group. In practice, however, programmers unify these patterns and define them as two variants of the Factory pattern. Presented implementation meets 3rd level of quality.

Elements that Factory patterns is made of (Gamma, Helm, Johnson & Vlissides, 1994):

- *Product* – declare the interface of objects generated by the factory, other names: product,
- *ConcreteProduct* – includes the implementation of the Product class, other names: a specific product,
- *Creator* – contains a declaration of the vendor methods that returns *Product* objects, other names: vendor,
- *ConcreteCreator* – override the method from *Creator* to return a copy of the *ConcreteProduct* class, other names: concrete vendor.

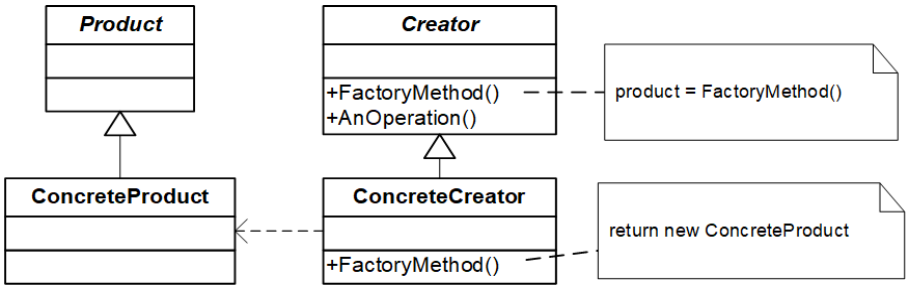


Fig. 3. Class diagram of Factory pattern, UML notation

The results of the assessment of the implementation of design patterns obtained during the experiment are presented in below, these are only parts of the code lower than the 3rd level of implementation:

- In command pattern – type is a class, the class should be replaced with an interface (limited ability to inherit in specific commands) – 2nd quality level,
- In command pattern – occurrence the method with a similar signature, the method name should be changed (possible a risk that the programmer may use a different Execute method than expected) – 2nd quality level,
- In command pattern – not all specific commands are included in the connection map, add the missing commands to the map (unused specific commands can be deleted or re-implanted) – 2nd quality level,
- In command pattern – there is a single call to the so-called in-line (the override type declaration was omitted), the call should be preceded by ICommand declarations (it disrupts the use of the pattern Command, limits the flexibility of the code, the execution of the selected commands is beyond the control of the Command pattern) – 1st quality level,

– In factory pattern – internal modifier (limited availability of the method), changes the access modifier to public (limited availability of the factory, will not be available outside the package, risk of reimplementation) – 2nd quality level.

In the case of the Command pattern, several errors occurred. Probably many of them would not be improved as part of further work, which in the case of expanding the software with new features in the future means more work. By using the method, the errors can be corrected even during the iteration of the experiment. In total, about 10% of the pattern code is below the 3rd level of implementation quality.

In the case of the Factory pattern there was only one error related to access modifiers. These types of errors are often the result of oversight of the implementers and, presumably, they would be successively repaired as part of other code work, however, that they are significantly extended in time. By assessing the quality of implementation of this pattern, the detected errors can be repaired earlier. In total, only 2% of the pattern code is below the 3rd level of implementation quality.

The cost of changes to be made resulting from the detected defects is small in the case of the Factory pattern. The cost of work without the use method Danyko was estimated at 20 man-hour, in case of the Command pattern. There contains time devoted to finding faults, testing, implementation work. After hearing the results of the quality assessment, the company team estimated the cost of work for 6 man-hour (implementation work), therefore the estimated savings in software development is 14 man-hour. The described time consumption does not take into account the time needed to develop reference implementations, however it is a one-time cost. Once developed models will be used many times in the production application of the method.

Obtained result, about 20% of time work of one worker in one iteration, is similar to previous experiment conducted with students (Wojszczyk, 2018), where obtained 28% time profit.

5. SUMMARY

The work presents verification of research results related to the method of assessing the quality of implementation of design patterns. Against the background of the comparative analysis, it was shown that the proposed method is from 45 to 57% less costly in the overall cost of use and from 60 to 61% less costly in the simulation of use for one year. As a result of another comparative analysis, it was also shown that the proposed method is more accurate than 25 to 68% compared to alternative methods.

The obtained results in practical experiment confirm the usefulness of the method in small, agile teams of programmers, where the costs of using such methods should be as low as possible, while maintaining the required accuracy. Further work anticipates automation of selected elements of the method, which will further reduce the cost of use. It is also planned to add additional elements to improve the accuracy of the method.

REFERENCES

Blewitt, A. (2006). *HEDGEHOG: Automatic Verification of Design Patterns in Java* (doctoral dissertation). University of Edinburgh, Edinburgh.

Gamma, E., Helm, R., Johnson, R., & Vlissides, J. (1994). *Design Patterns: Elements of Reusable Object-Oriented Software*. Boston: Addison-Wesley Professional.

Mehlitz, P. C., & Penix, J. (2003). Design for Verification Using Design Patterns to Build Reliable Systems. *Proc. Work. on Component-Based Soft. Eng*.

Metsker, S. J. (2004). *Design Patterns in C# 1st Edition*. Boston: Addison-Wesley Professional.

Nicholson, J., et al. (2014). Automated verification of design patterns: A case study. *Science of Computer Programming*, *80*, 211-222. doi:10.1016/j.scico.2013.05.007

Singh Rao, R., & Gupta, M. (2013). Design Pattern Detection by Greedy Algorithm Using Inexact Graph Matching. *International Journal Of Engineering And Computer Science*, *2*(10), 3658–3664.

Tsantalis, N., Chatzigeorgiou, A., Stephanides, G., & Halkidis, S. T. (2006). Design Pattern Detection Using Similarity Scoring. *IEEE Transactions on Software Engineering*, *32*(11), 896-908. doi:10.1109/TSE.2006.112

Wojszczyk, R., & Khadzhynov, W. (2017). The Process of Verifying the Implementation of Design Patterns—Used Data Models. In L. Borzemski, A. Grzech, J. Świątek, & Z. Wilimowska (Eds), *Information Systems Architecture and Technology: Proceedings of 37th International Conference on Information Systems Architecture and Technology – ISAT 2016 – Part I. Advances in Intelligent Systems and Computing* (*521*, pp. 103–116). Cham: Springer.

Wojszczyk R. (2018). The Experiment with Quality Assessment Method Based on Strategy Design Pattern Example. In: J. Świątek, L. Borzemski, & Z. Wilimowska (Eds.), *Information Systems Architecture and Technology: Proceedings of 38th International Conference on Information Systems Architecture and Technology – ISAT 2017. ISAT 2017. Advances in Intelligent Systems and Computing* (656, 103–112). Cham: Springer.

Applied Computer Science, vol. 15, no. 1, pp. 18–35
doi:10.23743/acs-2019-02

Submitted: 2018-12-06
Revised: 2019-01-01
Accepted: 2019-03-20

resource-constrained project scheduling problem, discounted cash flows, payment project scheduling, multi-stage project, milestones

Marcin KLIMEK [0000-0002-5912-197X]*

TECHNIQUES OF GENERATING SCHEDULES FOR THE PROBLEM OF FINANCIAL OPTIMIZATION OF MULTI-STAGE PROJECT

Abstract

The article presents the problem of scheduling a resource-constrained project with discounted cash flow maximization from the perspective of a contractor. The contractor's expenses (cash outflows for the contractor) are associated with the execution of activities. The client's payments (cash inflows for the contractor) are performed after fulfilling the agreed project stages. The following techniques are suggested for solving the problem: the activity right-shift procedure, the backward scheduling with the optimization of completion dates for the agreed project stages and the modified triple justification technique. The effect of these techniques of generating schedules is illustrated for an exemplary project. Finally, an experimental analysis of the proposed procedures is presented.

1. INTRODUCTION

One of the most often raised problems related to operational research in recent years is the Resource-Constrained Project Scheduling Problem (RCPSP). For the RCPSP can be used different optimization criteria: time criteria, namely the minimization of makespan, or financial criteria, namely the maximization of discounted cash flows etc. The discussion of the applied models may be found in the study (Hartmann & Briskorn, 2012). The analysis of cash flows related to the implemented project is particularly significant when planning the project. These cash flows are discounted in the majority of studies, their NPV (Net Present

* State School of Higher Education, Department of Computer Science, Sidorska 95–97, 21-500 Biala Podlaska, Poland, m.klimek@dydaktyka.pswbp.pl

Value) is calculated with the assumed discount rate. The maximization of the sum of discounted cash flows is the most frequent objective function in research taking into account the economic aspects in scheduling a project (Hartmann & Briskorn, 2012). The first optimization model with discounting cash flows Max-NPV for a project without resource constraints was proposed by Russell (1970). Numerous optimization models RCPSP-DC (RCPSP with Discounted Cash Flows) are analyzed for a project with limited resources (Hartmann & Briskorn, 2012; Herroelen, Reyck & Demeulemeester, 1997).

One of the analyzed problems of the RCPSP-DC is Payment Project Scheduling (PPS) (client (Dayanand & Padman, 1997; Herroelen, Reyck & Demeulemeester, 1997; Leyman & Vanhoucke, 2016). Research for the PPS problem include the determination of, among others, the number of tranches, the due dates and the amounts in particular payment tranches etc. A payment schedule, optimized from the point of view of the contractor (Klimek & Łebkowski, 2015, 2017; Mika, Waligóra & Węglarz, 2005; Ulusoy, Sivrikaya-Serifoglu & Sahin 2001), less frequently from the perspective of the client (Dayanand & Padman, 2001), is searched for in PPS problems. There are also attempts to find a compromise in the form of a payment implementation plan satisfactory both for the client and for the contractor (Bahrami & Moslehi, 2013; Ulusoy & Cebelli, 2000). The principles of settling works between the client and the contractor are determined and they may be the effect, for instance, of joint negotiations. The need for negotiations results from the fact that the client's and the contractor's interests with regard to payments for the project are usually divergent. The most favorable situation for the client is when the client pays the contractor only once after the end of the entire project, as in the Lump-Sum Payment model (LSP). The contractor prefers receiving the client's highest payments as soon as possible which may be allocated for funding the contractor's project works. The client's payments before the end of the project (Vanhoucke, Demeulemeester & Herroelen, 2003) are performed in the cash flow model assigned to events – Payment at Event Occurrences model (PEO). Events activating a payment are most often related to stages of works or activities, for instance payments are made after the end of selected activities or after the end of each activity in the Payments at Activities' Completion Times model (PAC). Payments spread evenly throughout the project, made in equal time intervals, are made in the Equal Time Intervals model (ETI) with a specific number of payments determined before building the schedule and the Progress Payments model (PP) with an unknown number of payments, depending on the duration of the project in the planned schedule. The last payment in each of the LSP, PEO, PAC, ETI, PP models is made upon the end of the project.

Models which include the use of gradual project settlement, with specified milestones, determined before project is planned by the client and the contractor (Klimek & Łebkowski, 2015; He, Wang, Jia & Xu, 2009; 2012; He & Xu, 2008) taking into account, for instance, the project progress, the costs of the execution

of activities, the costs of resource involvement etc. are developed. Earlier payments, before the project completion, for instance in stages, are unfavorable for the client. A bonus-penalty system is introduced during settlements to compensate the client's need to make earlier payments (He & Xu, 2008). Penalties are used for exceeding the agreed due dates for the project or its stages, while the bonuses are used for the completion of the project or its stages earlier than the agreed due date. Accurate due dates or time windows are defined in which the completion of an activity (stage) is neither awarded nor punished. The penalties and bonuses are to mobilize the contractor of works to execute the project as quick as possible. Without additional stimuli, the contractor prefers to delay the execution of particular activities (stages) with which costs are associated (subsequent expenses have a lower discounted value) The bonus-penalty system is effective from the perspective of the contractor if the benefits from the bonuses are higher than the contractor's costs related to the acceleration of completing an activity (stage), and the penalties for the lack of punctuality are higher than the contractor's benefits from a later completion of an activity (stage) The bonus-penalty system is effective from the perspective of the contractor if the bonuses for the contractor for an accelerated execution of activities (stages) are not higher than the client's benefits from an earlier execution of activities (stages), and the penalties for the lack of punctuality are higher than the client's losses related to delays in the execution of activities (stages).

Apart from settlements determined between the client and the contractor, the project's financial optimization from the perspective of the contractor takes into account other cash flows, for instance the contractor's expenses borne in connection with the execution of activities, the costs of resource involvement, transport and purchase of materials etc. The contractor's expenses are usually more frequent than receipts and their value depends on the incurred costs of works. Cash flows assigned to activities may be implemented at various moments of the activity's execution. However, it is most often assumed that expenses (cash outflows) are borne when the activity commences, while receipts (cash inflows) are acquired upon finishing the activity. Receipts/expenses related to the activity are also converted into a single cash flow performed directly before or directly after the end of the activity.

Various optimization models for projects with single-mode or multi-mode for executing the activities, performed with the use of renewable, double constrained, or non-renewable resources etc. are examined for RCPSP-DC (Leyman & Vanhoucke, 2016). Capital in Capital Constrained Project Scheduling Problem models (CCPSP) (Leyman & Vanhoucke, 2017; Smith-Daniels, Padman & Smith-Daniels, 1996) is one of the limited, non-renewable resources taken into account when building the schedule – the expenses and receipts need to balance one another at any moment of the project's duration, for instance activities may be executed only when financial funds for their execution obtained from the completion of previous works are available.

This article analyzes the single-mode RCPSP from the perspective of the contractor of the project, with expenses borne on account of the execution of activities and with receipts acquired from the client for the completed agreed stages of works. The problem with stage settlement of project works was not examined in this form in research related to RCPSP, except for the author's studies. Stage cash flows are examined for multi-mode RCPSP (He et al., 2009; He, Liu & Jia, 2012; He & Xu, 2008). The proposed optimization model for the purposes of the client's settlements with the contractor defines agreed stages (milestones) (Klimek, 2017; Klimek & Łebkowski, 2013, 2015, 2017): group of activities to be executed, due dates, the amount of payments for the execution of works as well as the amount of penalties decreasing the stage payments charged for a delayed completion of works. The proposed model with defined milestones may be useful in practice since it enables the settlement of the project depending on the degree of its completion. The milestone technique is used in practical projects to determine particularly important events on the way to achieving the project's objectives. It facilitates project management, increases the possibility to control its execution and the punctuality of works. According to the author, it may also be used for financial settlements between the contractor and the client.

It is recommended to schedule works for the financial optimization model of a multi-stage project so that the activities are started as late as possible, and the agreed project stages are completed as early as possible. The purpose of the study is to analyze the techniques of generating solutions, prepared by the author, dedicated for the examined model, taking into account the specific nature of stage settlements, namely the right shift of activities for schedule with a fixed resource allocation, backward scheduling with the optimization of completion times for project stages, or modified justification techniques. The effect of these techniques is illustrated for an exemplary project. The simple experimental analysis of the techniques of generating solutions is conducted for test instances from the PSPLIB library (Project Scheduling Problem LIBrary) (Kolisch & Sprecher, 1997) with additionally defined financial settlements of the project.

2. PROBLEM FORMULATION

A nonpreemptive single-mode RCPSP is analyzed in which the project is presented in the AON representation (Activity-On-Node) as a directed graph $G(V, E)$ in which V is the set of nodes corresponding to activities, and E is the set of arcs presenting precedence relations (Eq. 1) between activities (finish-start zero-lag precedence).

$$ST_i + d_i \leq ST_j, \qquad \forall (i, j) \in E \tag{1}$$

where: i – index of activity, $i = 1, \ldots, N_A$ (N_A – number of activities),
ST_i – starting time of activity i,
d_i – duration of activity i.

Activities are executed with the use of constrained, renewable resources the number of which is constant in time (Eq. 2). The number of used resources cannot exceed a_k at any time t, throughout the schedule's execution time.

$$\sum_{i \in J(t)} r_{ik} \le a_k, \qquad \forall t : t = 1, ST_{N_A+1}, \forall k : k = 1,..K \tag{2}$$

where: $J(t)$ – set of activities executed in the period $[t\text{-}1, t]$,
r_{ik} – demand of activity i for resource type $k = 1 \ldots K$,
K – number of types of resources,
a_k – number of available resources type k.

The applied optimization criterion is the maximization of the sum of discounted cash flows from the perspective of the contractor (Eq. 3).

$$F = \sum_{i=1}^{N_A} (CFA_i \cdot e^{-\alpha \cdot ST_i}) + \sum_{m=1}^{N_M} (CFM_m \cdot e^{-\alpha \cdot MT_m}) \tag{3}$$

where: F – objective function, sum of discounted cash flows,
CFA_i – contractor's expenses related to the execution of activity i,
m - index of project stage (milestone), $m = 1, \ldots, N_M$,
N_M – number of project stages,
CFM_m – client's payments for the completion of the m stage,
α – discount rate,
MT_m – completion date for the m stage in the current schedule.

The model does not contain periodic payments. It has been assumed that all the contractor's costs may be directly assigned to particular activities. Cash flows related to the project include cash inflows on account of the client's payments for the completion of project stages CFM_m as well as cash outflows associated with the involvement of resources and the performance of activities CFA_i, for instance for the purchase, transport of materials etc. necessary to complete the activity. It has been assumed that CFA_i expenses are borne exactly at the time ST_i in which the start of activity i is planned, while the client's payments CFM_m are made upon the completion of a given stage MT_m in the planned schedule.

Stage project settlements between the client and the contractor are used (Eq. 4–5).

$$MT_m = \max_{i \in MA_m}(FT_i), \qquad \forall m : m = 1,...,N_M \tag{4}$$

$$CFM_m = MP_m - MC_m \cdot \max(MT_m - MD_m, 0), \qquad \forall m : m = 1,...,N_M \tag{5}$$

where: FT_i – finish time of activity i ($FT_i = ST_i + d_i$),
MA_m – set of activities to be performed in the m stage of the project,
MP_m – amount of client's payment to the contractor for the completion of the m stage of the project,
MD_m – agreed due date for the m stage of the project,
MC_m – agreed unit penalty for exceeding the due date for the m stage of the project MD_m.

Groups of activities MA_m to be completed in a given stage of the project are determined. Same as for each stage due dates MD_m, the amount of the client's payments for the timely completion of the works MP_m, and principles for charging agreed penalties in the case of delays in the completion of stages, with determined unit penalties MC_m, agreed, for instance during negotiations between the client and the contractor.

Payments acquired by the contractor from the client for project stages are financial funds which may be allocated for current operations, for instance the purchase of materials necessary to complete subsequent activities, the employees' salaries etc. Increased payments from the client are not envisaged in the case of the completion of milestones earlier than planned in the agreement. In this case, an earlier acquisition of cash, the discounted value of which is higher, is the "bonus" for the contractor. The need to bear earlier expenses is compensated for the client by the introduction of agreed penalties for the lack of punctuality in the completion of project stages as well as the possibility to control the course of works during the project's execution.

The proposed model of stage settlements for project works may be useful in practice and beneficial both for the client and for the contractor. Its application may lead to a reduction in the lack of punctuality in the completion of project works which is a significant problem occurring during the execution of practical projects.

3. TECHNIQUES OF GENERATING SCHEDULES

A direct representation of solution for RCPSP is the vector of starting times of activities which may be used, for instance, to determine the sum of discounted cash flows of the project. When creating the schedule, solution is coded using other representations, more convenient to local search for solutions, such as an activity list, namely the permutation of activity numbers taking into account precedence relations. The activity list is transformed into a feasible schedule

(taking into account resource and precedence constraints) in direct representation with the use of the Schedule Generation Scheme (SGS) which include serial SGS and parallel SGS (Kolisch, 1996). The schedule may be determined by way of planning activities from the beginning of the activity list (forward scheduling) or from the end of the list by planning the activities as late as possible with the agreed due date for the project (backward scheduling)

The schedule determined with the use of SGS procedures may be improved in the case of the problem of the maximization of the sum of negative and positive discounted cash flows (as for the analyzed problem). The growth in NPV brings the earliest possible start of activities (stages) with assigned cash inflows and the latest possible start of activities (stages) with assigned cash outflows. Bi-directional SGS (Selle & Zimmermann, 2003), iterative shift algorithms which shift activities with negative cash flows to the right (for forward schedules) and/or activities with positive cash flows to the left (for backward schedules) etc. are used as techniques of generating solutions (Vanhoucke, Demeulemeester & Herroelen, 2001).

In a schedule suitable for the problem with the maximization of the sum of discounted cash flows analyzed in the article, the cash inflows, namely the client's payments for the completion of the agreed stages of works, should be acquired as soon as possible, while cash outflows, namely the contractor's expenses related to commenced activities, should be borne as late as possible. The growth in NPV brings the postponement these activities in time (according to the principle *As Late As Possible* – ALAP), the delayed start of which does not change the completion times of project stages.

According to the author's knowledge, there are no procedures generating schedules dedicated for the examined matter. As a result, dedicated techniques for building solutions prepared by the author are suggested, based on known procedures, namely:

- the right shift of activities with a fixed resource allocation,
- backward scheduling with the optimization of completion times for the agreed project stages,
- the justification technique taking into account the due dates for the agreed project stages.

Subsequent sub-chapters describe particular techniques of generating schedules. Let us use an example to illustrate their effect as well as to explain the problem of the financial optimization of a multi-stage project.

Let the project consist of 8 activities performed with the use of one type of resource with availability equal to 10. This project in the Activity-On-Node representation (AON) is presented in Fig. 1 (nodes 0 and 9 represent dummy activities).

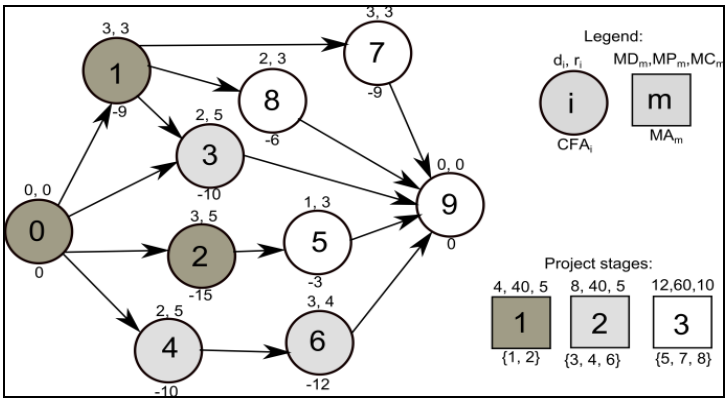


Fig. 1. Exemplary project in AON representation

The project has 3 defined stages, which consist of the following activities: MA_1 ={0, 1, 2}, MA_2 ={3, 4, 6}, MA_3 ={5, 7, 8, 9}. The due dates for stages are: MD_1 = 4, MD_2 = 8 and MD_3 = 12. The client's payments for the completed stages are determined on the basis of the amounts MP_1 = 40, MP_2 = 40, MP_3 = 60, which may be reduced by the costs of possible delays calculated on the basis of unit costs MC_1 = 5, MC_2 = 5, MC_3 = 10. The discount rate α = 0.01 is used in the calculations of the value of discounted cash flows.

The contractor of the project constructs a schedule for determined cash flows related to the project in which, from the contractor's perspective, the sum of discounted cash flows is maximized – the F function, taking into account precedence constraints and resource constraints. The schedules are built for solutions presented in the representation of the activity lists. Let us assume that the activity list {1, 5, 2, 3, 4, 6, 7, 8} is processed. The forward schedule generated using serial SGS for this activity list is presented in Fig. 2.

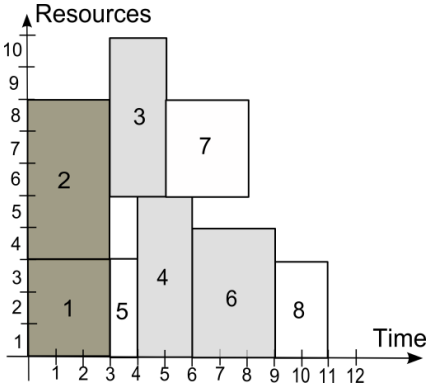


Fig. 2. The schedule determined with serial SGS for the activity list {1, 5, 2, 3, 4, 6, 7, 8}

The F objective function for the schedule from Fig. 2 is calculated as follows:

$$\sum_{i=1}^{N_A}(CFA_i \cdot e^{-\alpha \cdot ST_i}) = -\frac{9}{e^{0.01 \cdot 0}} - \frac{15}{e^{0.01 \cdot 0}} - \frac{10}{e^{0.01 \cdot 3}} - \frac{10}{e^{0.01 \cdot 4}} - \frac{3}{e^{0.01 \cdot 3}} - \frac{12}{e^{0.01 \cdot 6}} - \frac{9}{e^{0.01 \cdot 5}} - \frac{6}{e^{0.01 \cdot 9}}$$

$$= -71.57,$$

$$\sum_{m=1}^{N_M}(CFM_m \cdot e^{-\alpha \cdot MT_m}) = \frac{40}{e^{0.01 \cdot 3}} + \frac{40-5}{e^{0.01 \cdot 9}} + \frac{60}{e^{0.01 \cdot 11}} = 124.56,$$

$$F = -71.57 + 124.56 = 52.99.$$

The first and the third stage in the schedule are completed before the agreed due date which is beneficial for the contractor in relation with the increase in the discounted value of the client's payments. However, an untimely completion of the second stage of project stage is planned (MT_2 = 9 with the agreed due date MD_2 = 8), which diminishes the client's payments for this stage. Additionally, the growth in the project's NPV is possible resulting from starting the activities as late as possible keeping the due dates for stages.

3.1. Activity right-shift procedure

The first proposed method of generating schedules for the examined problem of the financial optimization of a multi-stage project is the activity right-shift procedure. Activity shifts for the S forward schedule take place with a fixed allocation of resources, for which it is easy to take into account resource constraints, it is possible to define in an unambiguous manner what changes to the schedule will be caused by the shifted start of each activity. Subsequent iterations analyze the right-shift of subsequent activities examined in the descending order of their starting times in the analyzed schedule. A given activity is shifted as long as this operation increases the value of the F objective function (Klimek & Łebkowski, 2015).

A variety of resource allocations to activities, characterized by various properties affecting the right shifts of activities and the quality of generated solutions measured by the value of the F objective function, may be generated for a given schedule (Klimek & Łebkowski, 2015). The problem of resource allocation for RCPSP is a strong NP-Hard problem, already with one type of resources (Leus & Herroelen, 2004; Deblaere, Demeulemeester, Herroelen & Van De Vonder, 2006). The allocation of resources to activities is analyzed with proactive, robust scheduling in which the objective, among others, is to minimize the number of additional arcs (Deblaere et al., 2006; Klimek & Łebkowski, 2011, 2013). A review of resource allocation procedures is presented in study (Deblaere et al., 2006).

Resource allocations with the smallest number of additional arcs are usually preferred for the analyzed problem. Additional order constraints resulting from the adopted resource allocation may diminish the number of activities the shift of which increases the value of the project's objective function. Right-shift procedures will be analyzed for the schedule from Fig. 2.

The allocation of resources generated with the use of a simple allocation procedure (Artigues, Michelon & Reusser, 2003), in which the activities are allocated to the first free chains related to subsequent resources, is presented in Fig. 3a.

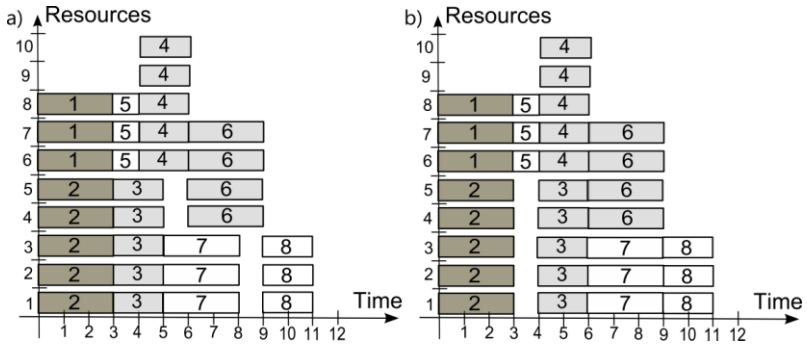


Fig. 3. Schedules: a) schedule with resource allocation, b) schedule determined with the use of the right shift procedure

Right-shifts of subsequent activities are analyzed for the allocation of resources from Fig. 3a: the shift of activities 8 and 6 does not increase the *F* value, the shift of activity 7 by one time unit increases *F* from 52.99 to 53.07, the shift of activity 4 does not increase the *F* value, the shift of activity 3 by one time unit increases *F* from 53.07 to 53.17, the shift of activities 5, 2 and 1 does not increase the *F* value, the shift algorithm finishes its operation. The schedule with right-shifts with $F = 53.17$ is presented in Fig. 3b.

A greater right-shift of activities 3 and 7 is impossible for the allocation of resources determined presented in Fig. 3a. Such operation is possible for the allocation found with the use of the RALS procedure (Resource Allocation with Local Search), in which an allocation which enables right-shifts of the highest number of activities improving the project's NPV is requested (Klimek & Łebkowski, 2015). The schedule with resource allocation determined with the use of the RALS procedure is presented in Fig. 4a.

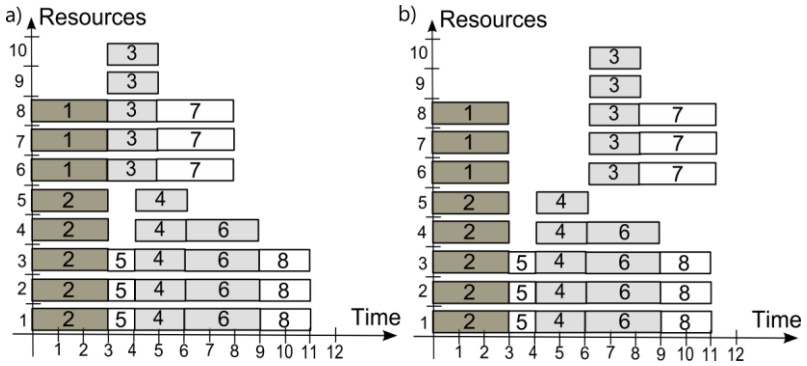


Fig. 4. Schedules: a) schedule with resource allocation determined with the use of the RALS procedure, b) schedule corrected with the use of the right-shift procedure

For resource allocation presented in Fig. 4a, the right-shift procedure will shift activity 7 by three time units (increase in F from 52.99 to 53.24) and will shift activity 3 by three time units (increase in F from 53.24 to 53.53). The schedule with right-shifts with F = 53.53 is presented in Fig. 4b.

The right-shift procedure does not introduce changes to the completion times of the project's stages. It may be effective when correcting schedules with the most beneficial completion times for the milestones. The optimum solution with F = 58.73 for the analyzed example (Fig. 5b) is found, for instance for a schedule determined with serial SGS for the activity list {1, 2, 3, 4, 5, 6, 7, 8} with resource allocation generated with the RALS procedure (Fig. 5a).

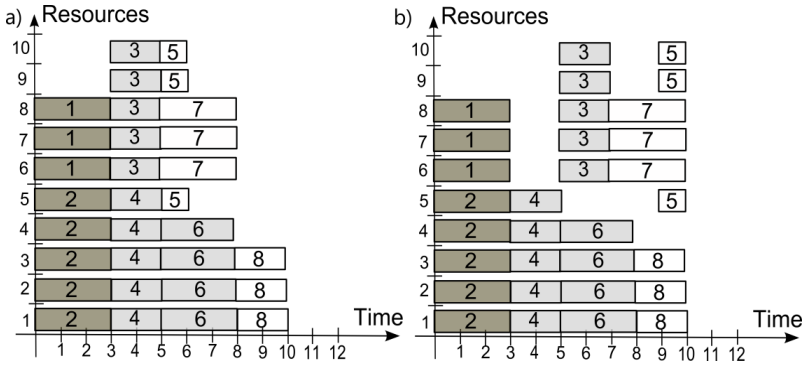


Fig. 5. Schedules: a) schedule generated for activity list {1, 2, 3, 4, 5, 6, 7, 8} with resource allocation determined with the use of the RALS procedure, b) schedule corrected with the use of the right-shift procedure

3.2. Backward scheduling

Another proposed procedure of generating solutions dedicated to the examined problem is backward scheduling with the optimization of completion times for project stages (Klimek & Łebkowski, 2017). This procedure includes serial SGS with backward planning of activities performed for the selected completion times for the project's stages MT_m iteratively shifted to the left. Shift operations are performed for subsequent stages, from the first to the last.

A baseline schedule is created for the processed activity list, assuming the planned completion dates for the stages MT_m equal to the agreed due dates MD_m. The completion dates for stages MT_m in the baseline schedule may be greater than the agreed due dates MD_m, if it is not possible to generate a feasible schedule with $MT_m = MD_m$ for each $m = 1, .., N_M$ for the processed activity list. The shift of a given stage takes place as long as this operation increases the value of the F objective function. Subsequent schedules created by the optimization procedure for completion dates for the agreed project stages for the analyzed project and the activity list {1, 5, 2, 3, 4, 6, 7, 8} are presented in Fig. 6a–c.

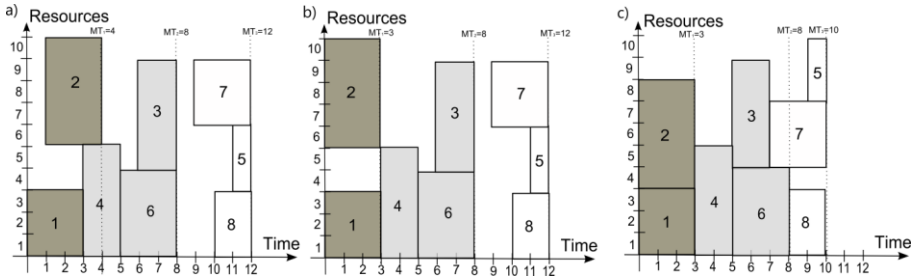


Fig. 6. Schedules: a) backward schedule generated for activity list {1, 5, 2, 3, 4, 6, 7, 8} using initial completion dates for stages: $MT_1 = 4$, $MT_2 = 8$, $MT_3 = 12$, b) schedule determined as a result of optimization of the completion date for the first stage: $MT_1 = 3$, $MT_2 = 8$, $MT_3 = 12$, c) Schedule determined as a result of optimization of completion dates for three project stages: $MT_1 = 3$, $MT_2 = 8$, $MT_3 = 10$

The backward schedule determined for the activity list {1, 5, 2, 3, 4, 6, 7, 8}, with completion dates for stages such as the agreed due dates, is presented in Fig. 6a. The value of the objective function for this schedule $F = 57.84$. The left-shift procedure of the project's stages starts with shifting the due date for the first stage. Assuming $MT_1 = 3$, a schedule with a greater value of the objective function $F = 58.08$ is generated, for $MT_1 = 2$ it is impossible to create a feasible schedule, the procedure proceeds to the optimization of the due date for the second stage MT_2. It is impossible to generate a feasible schedule for $MT_2 = 7$, the procedure proceeds to a left-shift of the project's third stage. In the third stage, assuming $MT_3 = 11$, the value of the objective function increases $F = 58.45$, assuming $MT_3 = 10$, the value of the objective function increases

F = 58.73. It is impossible to generate a feasible schedule within the due date MT_3 = 9, the procedure ends the first iteration of shifting the project's stages and starts its operation again from the first stage with assumed MT_1 = 3, MT_2 = 8, MT_3 = 10. No changes are made in the second iteration of the procedure, the algorithm finishes its operation.

The schedule determined after a unit shift of the first stage with the value of the objective function F = 58.08 is presented in Fig. 6b. The final schedule generated with the optimization of completion dates for all stages of the project with value of the objective function F = 58.73 is presented in Fig. 6c.

3.3. Justification techniques

Generating solutions relevant to the analyzed problem is also possible with the use of the justification techniques (Valls, Ballestin & Quintanilla, 2005): right justification (abbreviated to RJ) and left justification (abbreviated to LJ), which are used for RCPSP, among others, for the problem of the minimization of the project's duration or for the problem with defined due dates for activities. Justification techniques transform the schedule and often improve its quality. The justification of a given activity to the right (to the left) consists in determining the latest possible (earliest possible) starting time for such an activity, taking into account order constraints and resource constraints. LJ and LJ techniques are often combined, for instance double justification is used, RJ+LJ or LJ+RJ. The conducted analysis of justification techniques for exemplary schedules has shown that solutions of good quality are generated with the use of triple justification RJ+LJ+RJ. An effective strategy for the order of shifting the activities has been adopted in the case of justification, namely justification by extremes: the right (left) justification includes subsequent activities with the maximum finish time (minimum starting time) in the justified schedule. The RJ technique is modified: activities are shifted so as not to delay the current completion dates for the project's stages MT_m.

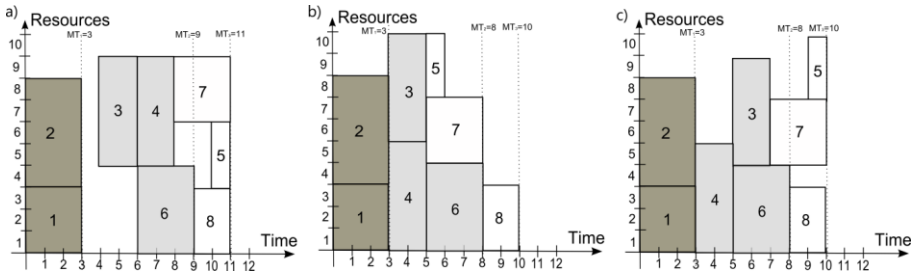


Fig. 7. Schedules: a) schedule from Fig. 2 after using RJ, b) schedule from Fig. 2 after using RJ+LJ, c) Schedule from Fig. 2 after using RJ+LJ+RJ

Let us assume that the schedule from Fig. 2 generated forward is amended with the use of serial SGS for the activity list {1, 5, 2, 3, 4, 6, 7, 8}. Subsequent transformations of the schedule with the use of triple justification RJ+LJ+RJ are presented in Fig. 7a–c.

Technique RJ is used at the beginning and it includes activities with the maximum finish time – subsequent activities 8, 6, 7, 4, 3, 5, 2, 1 (the activity with the higher number is analyzed earlier with an equal finish time) In the modified RJ, the latest possible starting time is determined for the justified activity, taking into account the precedence relations and resource relations as well as the current completion time of a project stage to which this activity belongs (MT_1 = 3, MT_2 = 9, MT_3 = 11). The schedule presented in Fig. 7a with better quality F = 53.72, due to a delayed start of activities 3, 4, 5 and 7, is created as a result of RJ.

Technique LJ is performed for the schedule after RJ. LJ includes activities with the minimum starting time in the schedule from Fig. 7a – subsequent activities 1, 2, 3, 4, 7, 5, 8 (the activity with the lower number is analyzed earlier with an equal starting time). The earliest possible starting time is determined for the justified activity during LJ, taking into account the precedence relations and resource relations. The schedule presented in Fig. 7b with a higher value of the F objective function is created as a result of LJ, due to an earlier completion of the second and third stage (MT_2 = 8, MT_3 = 10) despite an earlier start of activities 3, 4, 5, 6, 7 and 8.

The schedule after RJ+LJ may be improved by the repeated application of the modified RJ. RJ includes activities with the maximum finish time in the schedule from Fig. 7b – subsequent activities 8, 7, 6, 5, 4, 3, 2, 1 for which the starting time is determined taking into account current completion dates for project stages MT_1 = 2, MT_2 = 8, MT_3 = 10). The schedule presented in Fig. 7c with the highest value F = 58.73 is created as a result of RJ, due to a delayed start of activities 3, 5 and 7.

4. EXPERIMENTS

The simple experiments were performed with the use of an application implemented in the C# language run on a PC computer with an Intel Core processor i7-4770 CPU 3.4 GHz, 8 GB RAM. 480 test instances from the set J30 (projects with 30 activities) as well as 480 instances from the set J90 (projects with 90 activities) were used from the PSPLIB (Kolisch & Sprecher, 1997). Three agreed stages are defined for each project from PSPLIB created on the basis of the S schedule generated with the use of serial SGS for the activity list {1, 2, …, 30} for the set J30 or {1, 2, …, 90} for the set J90. The makespan of the project in the S baseline schedule is calculated and marked with T.

The agreed due dates for the stages are determined as $MD_1 = T/3$, $MD_2 = 2T/3$ as well as $MD_3 = T$. Then, sets of activities to be executed in particular stages are created and determined on the basis of the S schedule (Klimek & Łebkowski, 2017):

- the set MA_1 contains all activities the completion time of which is lower or equal to MD_1,
- the set MA_2 contains all activities the completion time of which is lower or equal to MD_2 and greater than MD_1,
- the set MA_3 includes the remaining activities which do not belong to MA_1 or MA_2.

The data for determining the cash flows are determined for each test instance as follows:

- the amounts of the client's agreed payments are $MP_1 = 60$, $MP_2 = 60$, $MP_3 = 120$,
- the agreed unit penalties $MC_1 = 1.5$, $MC_2 = 1.5$, $MC_3 = 3$,
- the costs of the execution of activities CFA_i are calculated in proportion to the total demand for resources and the duration of a given activity, while the sum CFA_i for all activities amounts to 100.

The discount rate adopted in experiments $\alpha = 0.01$.

The aim of the experiments is to evaluate the effectiveness of the developed techniques of generating solutions. Random sampling is used – 1000 activity lists are generated and schedules are created for them with the use of serial SGS or parallel SGS as well as the activity right-shift procedure with a fixed allocation of resources, backward scheduling with the optimization of completion dates for agreed project stages or the modified justification. A schedule with the highest value of the F objective function from among the 1000 analyzed solutions is determined for each technique. The experiments are conducted two times due to the stochastic nature of the calculations. The results of experiments are presented in Table 1.

Tab. 1. Results of experiments

		FS		FS + RS		BS	FS+RJ		FS+RJ+LJ+RJ	
		ser	**par**	**ser**	**par**	**ser**	**ser**	**par**	**ser**	**par**
J30	Av_F, 1st run	75.12	74.08	75.56	74.65	77.22	76.55	75.69	77.33	76.87
	Av_F, 2nd run	75.20	74.06	75.63	74.60	77.23	76.62	75.66	77.36	76.85
	Nr_best , 1st run	0	0	19	18	300	194	137	308	253
	Nr_best, 2nd run	0	0	12	17	291	185	134	311	245
	CPU time [sec.]	0.01	0.04	0.14	0.16	0.19	0.04	0.07	0.09	0.13
J90	Av_F, 1st run	42.25	44.32	42.75	44.88	51.31	45.67	47.63	51.66	51.35
	Av_F, 2nd run	42.18	44.28	42.68	44.84	51.36	45.63	47.62	51.56	51.41
	Nr_best, 1st run	0	0	0	0	145	19	8	192	111
	Nr_best, 2nd run	0	0	0	0	151	22	9	179	123
	CPU time [sec.]	0.05	0.37	2.08	2.26	0.96	0.30	0.63	0.65	0.97

where: Av_F – the average value of the objective function after 1000 runs, Nr_best – the number of solutions identical to the best solution found by all algorithms analysed (for 480 test instances), FS – forward scheduling, RS – activity right-shift procedure, BS – backward scheduling, ser – serial SGS, par – parallel SGS.

The highest average value of the *F* objective function, both for projects from the set J30 and from the set J90, was achieved for a procedure using the triple justification RJ+LJ+RJ with serial SGS. This procedure found 308 or 311 (192 or 179) best solutions in two experimental studies from among solutions generated by all analyzed algorithms for the 480 examined test instances from the set J30 (J90).

Effective techniques of generating of solutions include backward scheduling with the optimization of completion times for project stages or the triple justification of solutions. The least effective and the most costly procedure in terms of computation is the activity right-shift procedure.

Better schedules for the set J30 are generated with the use of serial SGS. Solutions of a higher quality for the set J90 are generated with the use of parallel SGS, while the application of the triple justification brings better results for schedules created with the use of serial SGS.

5. SUMMARY

The article analyses the problem of the maximization of discounted cash flows of a multi-stage project from the perspective of the contractor. The problem and the techniques of generating relevant schedules are illustrated. An experimental analysis of the developed procedures, which determined effective techniques of generating solutions, was conducted, namely backward scheduling with the optimization of completion dates for project stages, triple justification.

The proposed model of stage settlements for project works may be useful in practice and beneficial both for the client and for the contractor. Its application may lead to a reduction in the lack of punctuality in the completion of project works which is a significant problem occurring during the execution of practical projects. Further works focus on comparing the effectiveness of various justification strategies as well as on the use of effective techniques of generating solutions in more advanced metaheuristics, namely simulated annealing.

REFERENCES

Artigues, C., Michelon, P., & Reusser, S. (2003). Insertion techniques for static and dynamic resource-constrained project. *European Journal of Operational Research*, *149*(2), 249–267. doi:10.1016/S0377-2217(02)00758-0

Bahrami, F., & Moslehi, G. (2013). Study of payment scheduling problem to achieve client-contractor agreement International. *Journal of Advanced Manufacturing Technology*, *64*(1), 497–511. doi:10.1007/s00170-012-4023-5

Dayanand, N., & Padman, R. (1997). On modelling payments in projects. *Journal of the Operational Research Society*, *48*(9), 906-918. doi:10.1057/palgrave.jors.2600440

Dayanand, N., & Padman, R. (2001). Project contracts and payment schedules: The client's problem. *Management Science*, *47*(12), 1654-1667. doi: 10.1287/mnsc.47.12.1654.10242

Deblaere, F., Demeulemeester, E., Herroelen, W., & Van De Vonder, S. (2006). Proactive resource allocation heuristics for robust project scheduling. *Research report KBI_0608*, K.U. Leuven. doi:10.2139/ssrn.870228

Hartmann, S., & Briskorn, D. (2012). A Survey of Variants and Extensions of the Resource-Constrained Project Scheduling Problem. *European Journal of Operational Research*, *207*(1), 1–14. doi:10.1016/j.ejor.2009.11.005

He, Z., Liu, R., & Jia, T. (2012). Metaheuristics for multi-mode capital-constrained project payment scheduling. *European Journal of Operational Research*, *223*(3), 605–613. doi:10.1016/j.ejor.2012.07.014

He, Z., Wang, N., Jia, T., & Xu, Y. (2009). Simulated annealing and tabu search for multimode project payment scheduling. *European Journal of Operational Research*, *198*(3), 688–696. doi:10.1016/j.ejor.2008.10.005

He, Z., & Xu, Y. (2008). Multi-mode project payment scheduling problems with bonus penalty structure. *European Journal of Operational Research*, *189*(3), 1191–1207. doi:10.1016/j.ejor.2006.07.053

Herroelen, W., Reyck, B. D., & Demeulemeester, E. (1997). Project network models with discounted cash flows: A guided tour through recent developments. *European Journal of Operational Research*, *100*(1), 97–121. doi:10.1016/S0377-2217(96)00112-9

Klimek, M. (2017). Priority algorithms for the problem of financial optimisation of a multi stage project. *Applied Computer Science*, *13*(4), 20–34. doi:10.23743/acs-2017-26

Klimek, M., & Łebkowski, P. (2011). Resource allocation for robust project scheduling. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *59*(1), 51–55. doi:10.2478/v10175-011-0008-z

Klimek, M., & Łebkowski, P. (2013). Robustness of schedules for project scheduling problem with cash flow optimization. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *61*(4), 1005–1015. doi:10.2478/bpasts-2013-0108

Klimek, M., & Łebkowski, P. (2015). Heuristics for project scheduling with discounted cash flows optimization. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *63*(3), 613–622. doi:10.1515/bpasts-2015-0072

Klimek, M., & Łebkowski, P. (2017). Financial optimisation of the scheduling for the multi-stage project. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *65*(6), 899–908. doi:10.1515/bpasts-2017-0097

Kolisch, R. (1996). Serial and parallel resource-constrained project scheduling methods revisited: Theory and computation. *European Journal of Operational Research*, *90*(2), 320–333. doi:10.1016/0377-2217(95)00357-6

Kolisch, R., & Sprecher, A. (1997). PSPLIB - a project scheduling library. *European Journal of Operational Research*, *96*(1), 205–216. doi:0.1016/S0377-2217(96)00170-1

Leus, R., & Herroelen, W. (2004). Stability and resource allocation in project planning. *IIE Transaction*, *36*(7), 667–682. doi:10.1080/07408170490447348

Leyman, P., & Vanhoucke, M. (2016). Payment models and net present value optimization for resource-constrained project scheduling. *Computers & Industrial Engineering*, *91*, 139–153. doi:10.1016/j.cie.2015.11.008

Leyman, P., & Vanhoucke, M. (2017). Capital- and resource-constrained project scheduling with net present value optimization. *European Journal of Operational Research*, *256*(3), 757–776. doi:10.1016/j.ejor.2016.07.019

Mika, M., Waligóra, G., & Węglarz, J. (2005). Simulated annealing and tabu search for multi-mode resource-constrained project scheduling with positive discounted cash flows and different payment models. *European Journal of Operational Research*, *164*(3), 639–668. doi:10.1016/j.ejor.2003.10.053

Russell, A. H. (1970). Cash flows in networks. *Management Science*, *16*(5), 357–373. doi:10.1287/mnsc.16.5.357

Selle, T., & Zimmermann, J. (2003). A bidirectional heuristic for maximizing the net present value of large-scale projects subject to limited resources. *Naval Research Logistics*, *50*(2), 130-148. doi:10.1002/nav.10052

Smith-Daniels, D. E., Padman, R., & Smith-Daniels, V. L. (1996). Heuristic scheduling of capital constrained projects. *Journal of Operations Management*, *14*(3), 241–254. doi:10.1016/0272-6963(96)00004-6

Ulusoy, G., & Cebelli, S. (2000). An equitable approach to the payment scheduling problem in project management. *European Journal of Operational Research*, *127*(2), 262–278. doi:10.1016/S0377-2217(99)00499-3

Ulusoy, G., Sivrikaya-Serifoglu F., & Sahin, S. (2001). Four Payment Models for the Multi-Mode Resource Constrained Project Scheduling Problem with Discounted Cash Flows. *Annals of Operations Research*, *102*, 237-261. doi:10.1023/A:1010914417817

Valls, V., Ballestin, F., & Quintanilla, S. (2005). Justification and RCPSP: a technique that pays. *European Journal of Operational Research*, *165*(2), 375–386. doi:10.1016/j.ejor.2004.04.008

Vanhoucke, M., Demeulemeester, E., & Herroelen, W. (2003). Progress payments in project scheduling problems. *European Journal of Operational Research*, *148*(3), 604–620. doi:10.1016/S0377-2217(02)00452-6

Vanhoucke, M., Demeulemeester, E., & Herroelen, W. (2001). Maximizing the net present value of a project with linear time-dependent cash flows. *International Journal of Production Research*, *39*(14), 3159-3181. doi:10.1080/00207540110056919

Applied Computer Science, vol. 15, no. 1, pp. 36–48
doi:10.23743/acs-2019-03

Submitted: 2019-01-15
Revised: 2019-02-05
Accepted: 2019-03-09

knee joint, kinetic chain, signals, articular cartilage

Robert KARPIŃSKI [0000-0003-4063-8503]*,
Anna MACHROWSKA [0000-0003-3289-2421]*,
Marcin MACIEJEWSKI [0000-0001-9116-5481]**

APPLICATION OF ACOUSTIC SIGNAL PROCESSING METHODS IN DETECTING DIFFERENCES BETWEEN OPEN AND CLOSED KINEMATIC CHAIN MOVEMENT FOR THE KNEE JOINT

Abstract

The paper presents results of preliminary research of analysis of signals recorded for open and closed kinematic chain in one volunteer with chondromalacia in both knees. The preliminary research was conducted in order to establish the accuracy of the proposed method and will be used for formulating further research areas. The aim of the paper is to show how FFT, recurrence plots and recurrence quantification analysis (RQA) can help in bioacoustic signals analysis.

1. INTRODUCTION

We are living in the age of galloping technical progress. Computers are getting smaller and faster, communication is instantaneous and we are able to cure more and more diseases. Unfortunately, such a situation also leads to negative consequences (Maciejewski et al., 2014). We are spending more time sitting down and not performing any physical activities, and the average age in western population

* Department of Machine Design and Mechatronics, Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland, r.karpinski@pollub.pl, a.machrowska@pollub.pl

** Institute of Electronics and Information Technology, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland, m.maciejewski@pollub.pl

is increasing. Also, obesity is now a major factor. This results in the increased prevalence of cardiovascular conditions (Maciejewski, Dzierżak, Surtel & Saran, 2016; Maciejewski, Surtel & Dzida, 2015) and problems with joints and muscles. Especially the knee is a joint that can easily fail in an overweight patient, resulting in problems with everyday life.

Unfortunately, it is not easy to diagnose early symptoms of knee cartilage degeneration. Usual methods include ultrasonography, magnetic resonance and arthroscopy. In some cases, computer tomography can be performed. These methods generate significant costs and can sometimes provide inconclusive results. On the other hand, the procedure of arthroscopy is relatively cheap and can give precise information, but is an invasive procedure, and, as such, results in damage to some tissue. Due to these factors it is vitally important to develop and test a precise, cheap and simple procedure to assess the level of joint tissue degeneration. By early diagnosis it is possible to mitigate some consequences by introducing proper supplementation and physical therapy.

Therefore, the progress in the development of numerical methods related to the processing of acoustic signals used in medicine can make it possible to collect and analyze the necessary data without the need for costly or invasive tests on humans (Karpiński, Jaworski, Jonak & Krakowski, 2019).

Understanding and determining the nature of the test signal provides the basis for the considerations related strictly to data analysis. This is particularly important in the case of discovering new areas, where it is difficult to make both quantitative and qualitative analyzes, based only on the present state of knowledge. Therefore, it is necessary to illustrate the characteristics of the studied waveforms. The above concept is reflected in the preliminary studies on vibroacoustic processes recorded for the cartilage tissues of the knee joint.

Due to the individualized nature of muscular activity of people with degenerative changes of joints, including damaged joint relieving, it seems particularly important to take up the subject of recorded signals analysis for open and closed kinematic chain cases.

2. KNEE ACOUSTIC EMISSION

Knee joint is the biggest and most complex joint in the human body and one of the most susceptible to mechanical injuries and degenerative changes. This joint is a combination of three bones: the tibia, fibula, and femur. The joint includes a patella. The knee is the joint that transmits the loads that occur when moving between these elements. The major part taking the load in the knee joint is a thick layer of hyaline cartilage (6–7 mm), which under physiological conditions provides almost frictionless movement between the forming bones (Zubrzycki, Karpiński & Górniak, 2016; Karpiński et al., 2019). The occurrence of frequent excessive overloads, mechanical injuries and disturbances of lubricating properties

of synovial fluid cause accelerated wear and degeneration of cartilage structures, which may result in deterioration of both quantitative and qualitative aspects of joint functioning (Krakowski et al., 2018).

Typical diagnostic imaging methods such as magnetic resonance imaging, ultrasonography or computed tomography usually generate high costs and limited availability especially for patients treated in smaller medical centers. In addition, in relation to cartilage structures, they are characterized by insufficient accuracy and diagnostic sensitivity. Therefore, it is extremely important to look for alternative methods to assess the degree of damage/degeneration of joint surfaces, for example, an assessment based on the generated vibroacoustic processes related to the change in the characteristics of the mechanical structures included in the joint (Kręcisz & Bączkowicz, 2018). The analysis of the generated vibroacoustic processes can provide the information about the tribological properties of the joint, the quantity and properties of the synovial fluid and the functioning of articular cartilage during movement which is omitted in classical imaging diagnostics (Bączkowicz, Kręcisz & Borysiuk, 2019; Kim, Seo, Kang & Song, 2009; Wiens, Prahalad & Inan, 2016).

Data presented in the following works (Bączkowicz et al., 2019; Choi, Ahn, Ryu, Nagao & Kim, 2018; Goodacre et al., 2018; Rangayyan, Oloumi, Wu & Cai, 2013; Shark, Chen & Goodacre, 2010, 2011) show that there is a strong relationship between the level f vibroacoustic emission and the degree of damage to the joint surfaces of the knee joint. It has been reported, that knee joints of patients with degenerative changes produce vibroacoustic emissions with higher frequency, higher peaks and longer duration compared to healthy knees. It is believed that the analysis of acoustic signals provides specific information about the tribological properties of the joint, related to, inter alia, the state of vitreous cartilage and / or rheological features of synovial fluid. Diagnostic methods based on generated vibroacoustic processes allow physicians to assess joint performance under normal operating conditions, with particular emphasis on its functions in motion. This allows for a significant extension of therapeutic activities such as the selection of exercises and pharmacological treatment. The analysis of vibroacoustic processes provides us with information on the quality of traffic and its dynamic parameters, which is a significant extension of imaging methods (Bączkowicz & Majorczyk, 2014).

Currently, there are no strict guidelines on how to measure vibroacoustic processes generated by the knee joint, or for the measuring system itself and the methods of processing recorded signals. Some authors suggest measurements in an open kinematic chain (Bączkowicz et al., 2019; Kim et al., 2009; Wu et al., 2016). The measurements are carried out in a sitting position for repetitive movements. The use of an open kinematic chain may play a particularly important role in cases of patients with advanced degenerative changes affecting the limitation of the range of motion in the joint. Some of the studies include tests in a closed kinematic chain, the range of motion will involve repeated sit – stand – sit

movements (Shark et al., 2011; Wiens et al., 2016). From a biomechanical point of view, movements performed in a closed and open kinematic chain generate various patterns of muscle activity, thus changing the distribution of forces and moments acting on the elements of the knee (Adouni & Shirazi-Adl, 2009). The aim of the work is to compare the results of analyzes for the waveforms recorded in the open and closed kinematic chain using typical signal processing methods and recursive graphs.

3. SIGNAL ANALYSIS

Signal analysis in a broader sense can be performed in time domain, frequency domain or using an approach in between. Time analysis usually focuses on calculating signal power, average value, median, variance, autocorrelation or fitting an autoregressive model. Also, trend analysis is performed in time domain. Analysis in time domain is usually the first step during processing and can give some idea on the type and character of signal. Nevertheless, when audio signals, or, in broader sense, vibrations are involved, it is necessary to perform calculations in frequency domain. The most popular frequency analysis methods involve Fourier analysis and wavelet transform.

3.1. Fourier analysis

Fourier analysis is a well-tested and widely used signal processing method aimed at representing the signal as a sum of trigonometric functions, most frequently sine and cosine. It allows for fast bandwidth calculation, signal filtration by decomposition, thresholding of chosen parameters and synthesis, noise removal and generation of spectrograms. Due to the nature of signal processing begin done by means of digital computing Fast Fourier Transform, or FFT, is used frequently to reduce numerical complexity by a significant factor. The transform results in a series of numerical values corresponding to amplitudes of sine vibrations for different frequencies in the signal. This series represents the whole time period of the analyzed signal. Such an approach can often result in loss of information about short, rare artifacts in the signal due to averaging. To counter this problem the idea of Short Time Fourier Transform, or STFT. In this case FFT is performed in a time window shorter than the total length of signal. This can be done by continuous or discrete time STFT. In the first case the position of the time window, usually Hann or Gaussian, changes by one sample every time the calculation is performed, in the second case the signal is broken into chunks which usually overlap to reduce artifacts, and FFT is performed for each chunk. Continuous time STFT produces more data and is more time consuming, while discrete time STFT can result in some omissions, so a proper method should be chosen wisely.

3.2. Recurrent plots, recurrence quantification analysis

Recurrent plot (RP) is a technique nonlinear signal analysis at dynamical approaches (Litak, Gajewski, Syta & Jonak, 2008; Litak, Syta, Gajewski & Jonak, 2010; Litak, Syta & Rusinek, 2011; Syta, Jonak, Jedliński & Litak, 2012). It is a representation of the results in the form of the symmetric N x N matrix, shown by the points symbolizing the presence of recursion. RP are a kind of visualization of the repeatability of the states of the studied dynamic system, where a phase space trajectory visits at the same area in the phase space. According to Takens (Takens, 1981), the phase space trajectory can be reconstructed from a time series by the time delay embedding. Recurrence states in the phase space located at recurrence plot are signed as black dots. There are various possibilities of the character of the examined waveform. The appearance of diagonal lines on RP means states where analyzed parts of the phase trajectory run parallel. Other possibilities include existence of periodic recurrent structures specific to periodic and quasi-periodic systems. Research focused on recurrence plots provide a wide range of current structures analysis. By means of diagonal lines length histogram, certain measures relevant for recurrence quantification analysis are determined. The most popular of them are: recurrence rate (RR), determinism (DET), maximal diagonal line length (LMAX), trend (TREND), entropy (ENTR), laminarity (LAM) and trapping time (TT). Recurrence rate parameter informs about the density of the recurrence points in the entire recurrence plot, it measures the probability of the recurrence of a certain state. Determinism specifies the number of recursive points forming linear segments parallel to the main diagonal line of the diagram, the presence of them reveals that the analyzed phenomenon is deterministic. The LMAX parameter determines the length of the longest diagonal line. Measure called trend provides information about the non-stationarity of the studied process and about the existence of a linear or periodic trend of process changes. Shannon entropy (Shannon, 1948) (ENTR) is the measure of the complexity of the deterministic structure in the system. Its high value is specific to dynamic periodic behavior, low ENTR values corresponds to chaotic systems. Laminarity parameter corresponds to share of recurrent states. This measure shows stability of the system behavior, low LAM value could indicate intermittency. Finally, trapping time refers to the average length of vertical lines, it shows the time of the remaining in a specific state.

4. MATERIALS AND METHODS

The tests were performed on a 36 year old white causasian female with diagnosed chondromalacia in both knees with the pain being significantly greater in the right knee. The patient used to take part in intense physical activities between the age of 20 and 30. During the test session both knees were independently tested. Three cases were recorded per knee, including slow and fast knee straightening while seated (open kinematic chain) and slow bodyweight squats (closed kinematic chain). The measurement system is presented below.

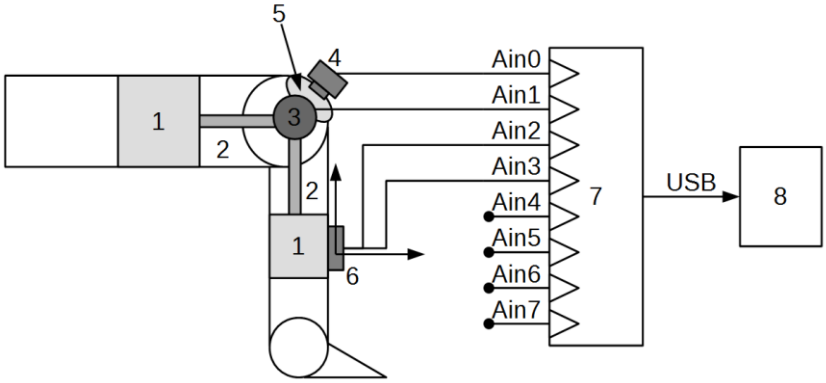


Fig. 1. Measurement system: 1 – elastic sleeve with Velcro regulation, 2 – rigid struts for attachment of the rotary encoder 3, 4 – solid body microphone placed on the skin directly touching the kneecap 5, 6 – inertial measurement unit for position estimation, 7 – analogue interface card for signal acquisition, 8 – computer used for data recording

The signal was sampled at 1kS/second for 30 seconds. The analogue to digital converter resolution was set at 16 bits. At 5V reference voltage this equated to about 76 microvolts resolution. The position of the microphone was chosen after knee palpation during movement to maximize the amplitude of vibrations. Signals recorded from the left knee are shown on the figure below.

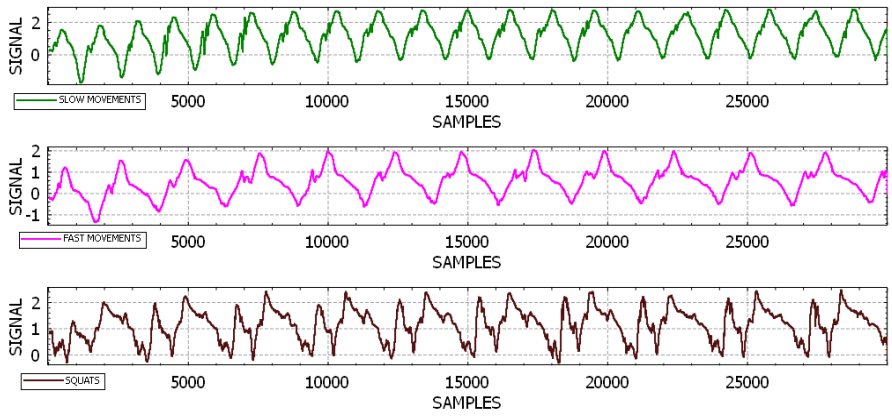


Fig. 2. Acoustic signals recorded from the left knee

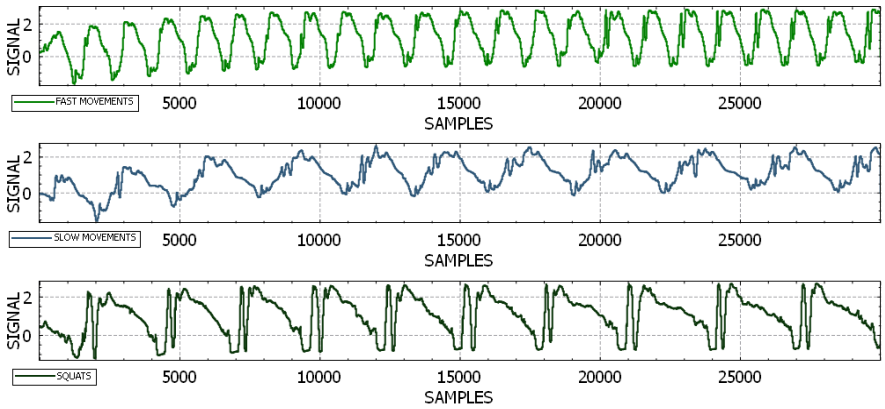


Fig. 3. Acoustic signals recorded from the right knee

5. RESULTS

The results were obtained using Matlab software and recurrence plot and recurrence quantification analysis toolbox (Chen & Yang, 2012; Yang, 2011; *Tool box of recurrence plot and recurrence quantification analysis – File Exchange – MATLAB Central*, n.d.). Fourier analysis was performed using Fast Fourier Transform with timebase of 1 kHz and the spectrum was limited from 0.2 to 6 Hz. In all the spectrum plots the basic frequency of knee movements is visible as the main peak. The spectrums show greater levels of higher order components for the right knee, especially in the closed kinematic chain during squats. This correlates with higher level of creaking of the right knee due to the tissue degeneration.

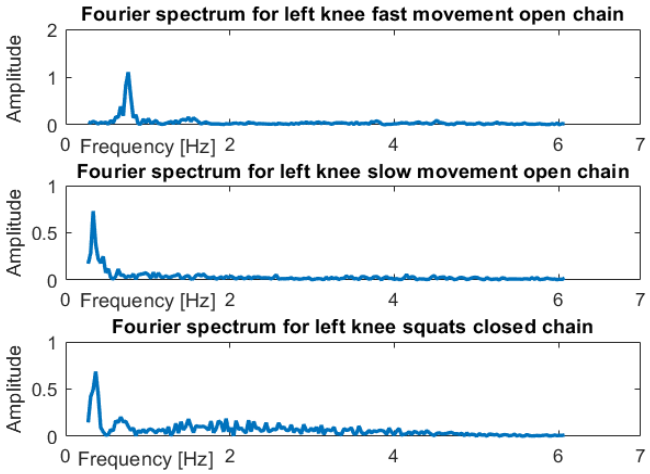


Fig. 4. Spectrums of signal acquired during left knee movement

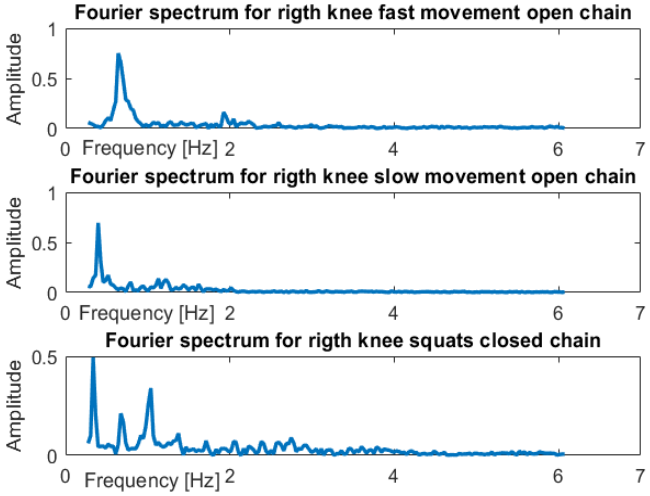


Fig. 5. Spectrums of signal acquired during left knee movement

Figure 4 shows left leg movements during the straightening (opened kinematic chain) and bodyweight squats movement – closed kinematic chain. Respectively, for right limb straightening movements and bodyweight squats movements FFT plots were visualized by figure 5. Recurrence plots presented on figure 6 are connected with left leg straightening movement (opened kinematic chain). Figure 7 shows recurrence plot of bodyweight squats movement for left limb. Figure 8 visualizes recurrent plots of opened kinematic chain movement for right leg. Recurrence plot of closed kinematic movement for right limb was presented on figure 9.

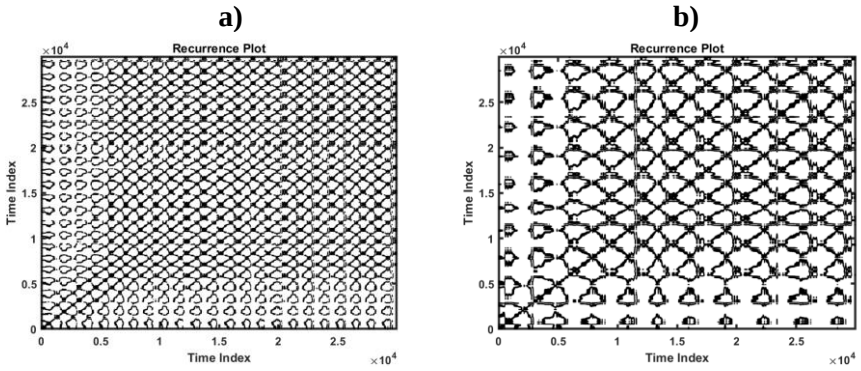


Fig. 6. Recurrence plots of left limb straightening movement in opened kinematic chain: a) fast movement, b) slow movement

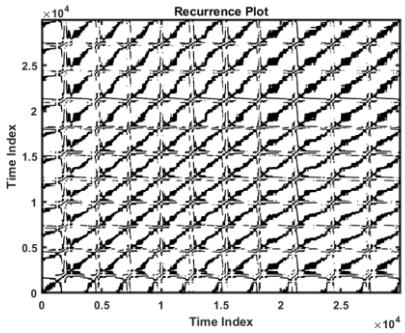


Fig. 7. Recurrence plot of left limb bodyweight squat movement in closed kinematic chain

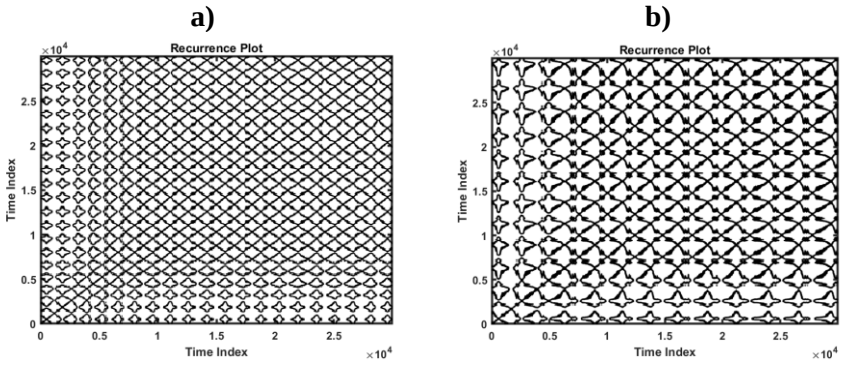


Fig. 8. Recurrence plots of right limb straightening movement in opened kinematic chain: a) fast movement, b) slow movement

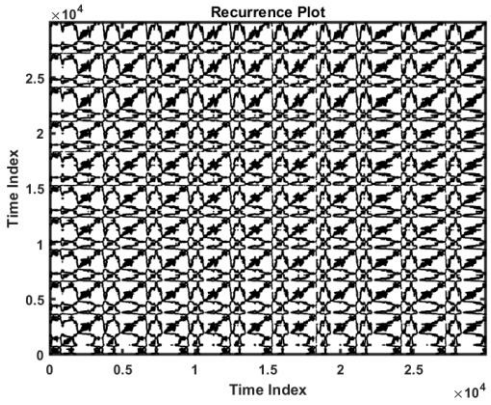


Fig. 9. Recurrence plot of left limb bodyweight squat movement in closed kinematic chain

Recurrence plots analysis shows a clear tendency to fading to the upper left and lower right corners in the case of acoustic signal registered for movement in open kinematic chain. Such feature could indicate nonstationarity or drift/trend component containing (Marwan, Carmenromano, Thiel & Kurths, 2007). In studied case of lower limb movements in opened and closed kinematic chains this phenomenon is related to the presence of initial muscle tension (closed kinematic chain) and lack of initial muscle tension for movement in opened kinematic chain. Structures visible on plots suggest that the signals have quasi-periodic character.

Results of conducted recurrence quantification analysis were placed in Tab.1.

Tab. 1. Recurrence quantification analysis

Type	RR	DET	LMAX	ENTR	TREND	LAM	TT
LFO	16.297	99.288	29983	6.639	-3.725e-18	99.564	53.266
LSO	22.600	99.791	29983	7.343	-1.770e-17	99.866	95.405
LSC	18.403	99.354	14682	7.068	-2.125e-18	99.623	90.181
RFO	19.032	99.565	29982	6.671	9.178e-18	99.738	60.001
RSO	31.054	99.775	29983	7.805	-4.100e-18	99.873	140.654
RSC	29.747	99.503	27413	7.050	2.657e-18	99.706	79.640

where: LFO – left knee fast movement in opened kinematic chain, LSO – left knee slow movement in opened kinematic chain, LSC – left knee bodyweight squat movement (close kinematic chain), RFO – right knee fast movement in opened kinematic chain, RSO – right knee slow movement in opened kinematic chain, RSC – right knee bodyweight squat movement (close kinematic chain)

Trapping time fast movement in opened kinematic chain: on right limb TT is more than on left one by 12%, in case of slow movement it is respectively 47%. Above relationship does not occur in closed kinematic chain. For bodyweight

squatting movement it was obtained inverse relationship: TT on left limb is more than on right one by 13%. Recurrent rate parameter describes repeatability of states degree. Carried out RQA analysis showed higher RR values for slow movements. LMAX measure has provided information related to registered data character. Lower values of this parameter were observed for movements in closed kinematic chain. It could indicate an increased degree of chaos in the investigated process. DET, LAM, ENTR and TREND values constitute the confirmation of recorded data periodic character.

6. CONCLUSION

The FFT data shows significant levels of higher order components in the signal during right knee movement in closed kinematic chain, which also corresponded to the greatest level of discomfort for the patient. It may be suggested, that it is connected to degradation of cartilage tissue in the knee area. It is impossible to provide hard evidence to support this claim, as more data needs to be collected and processed. Nevertheless, the results look promising.

From the kinematic chain type standpoint of RQA, the trapping time parameter is important. Longer TT for the opened kinematic chain movement could point to necessity of movement time extending due to the pain occurrence. The reverse dependency appearance (squatting movement in closed kinematic chain) confirms the increased discomfort for the examined limb existence. Squat is a type of highly individualized movement where differences are observed on the background of the anatomy, varying mobility degrees or finally the tissue damage size and pain. Therefore, the patient may shorten the time of passing through the given range during the squat movement (the angle of the limb position), where the greatest discomfort appears (Brinckmann, Hoefert & Jongen, 1981; Gilsanz et al., 1994; Marras, Jorgensen, Granata & Wiand, 2001).

REFERENCES

Adouni, M., & Shirazi-Adl, A. (2009). Knee joint biomechanics in closed-kinetic-chain exercises. *Computer Methods in Biomechanics and Biomedical Engineering*, *12*(6), 661–670. doi:10.1080/10255840902828375

Bączkowicz, D., Kręcisz, K., & Borysiuk, Z. (2019). Analysis of patellofemoral arthrokinematic motion quality in open and closed kinetic chains using vibroarthrography. *BMC Musculoskeletal Disorders*, *20*(1). doi:10.1186/s12891-019-2429-z

Bączkowicz, D., & Majorczyk, E. (2014). Joint motion quality in vibroacoustic signal analysis for patients with patellofemoral joint disorders. *BMC Musculoskeletal Disorders*, *15*, 426. doi:10.1186/1471-2474-15-426

Brinckmann, P., Hoefert, H., & Jongen, H. T. (1981). Sex differences in the skeletal geometry of the human pelvis and hip joint. *Journal of Biomechanics*, *14*(6), 427–430. doi:10.1016/0021-9290(81)90060-9

Chen, Y., & Yang, H. (2012). Multiscale recurrence analysis of long-term nonlinear and nonstationary time series. *Chaos, Solitons & Fractals*, *45*(7), 978–987. doi:10.1016/j.chaos.2012.03.013

Choi, D., Ahn, S., Ryu, J., Nagao, M., & Kim, Y. (2018). Knee Acoustic Emission Characteristics of the Healthy and the Patients with Osteoarthritis Using Piezoelectric Sensor. *Sensors and Materials*, *30*(8), 1629. doi:10.18494/SAM.2018.1877

Gilsanz, V., Boechat, M. I., Gilsanz, R., Loro, M. L., Roe, T. F., & Goodman, W. G. (1994). Gender differences in vertebral sizes in adults: biomechanical implications. *Radiology*, *190*(3), 678–682. doi:10.1148/radiology.190.3.8115610

Goodacre, J., Schlueter, D. K., Shark, L.-K., Spain, L., Platt, N., Platt, N., Mercer, J., Waterton, J. C., Bowes, M., Dixon, M., & Huddleston, J. (2018). Identifying Novel Acoustic Emission Biomarkers for Use in Knee Osteoarthritis Clinical Trials. *Rheumatology*, *57*(suppl_3), key075.321. doi:10.1093/rheumatology/key075.321

Karpiński, R., Jaworski, Ł., Jonak, J., & Krakowski, P. (2019). Stress distribution in the knee joint in relation to tibiofemoral angle using the finite element method. *MATEC Web of Conferences*, *252*, 07007. doi:10.1051/matecconf/201925207007

Kim, K. S., Seo, J. H., Kang, J. U., & Song, C. G. (2009). An enhanced algorithm for knee joint sound classification using feature extraction based on time-frequency analysis. *Computer Methods and Programs in Biomedicine*, *94*(2), 198–206. doi:10.1016/j.cmpb.2008.12.012

Krakowski, P., Gerkowicz, A., Pietrzak, A., Krasowska, D., Jurkiewicz, A., Gorzelak, M., & Schwartz, R. A. (2018). Psoriatic arthritis – new perspectives. *Archives of Medical Science*. https://doi.org/10.5114/aoms.2018.77725

Kręcisz, K., & Bączkowicz, D. (2018). Analysis and multiclass classification of pathological knee joints using vibroarthrographic signals. *Computer Methods and Programs in Biomedicine*, *154*, 37–44. doi:10.1016/j.cmpb.2017.10.027

Litak, G., Gajewski, J., Syta, A., & Jonak, J. (2008). Quantitative estimation of the tool wear effects in a ripping head by recurrence plots. *Journal of Theoretical and Applied Mechanics*, *46*(3), 521–530.

Litak, G., Syta, A., Gajewski, J., & Jonak, J. (2010). Detecting and identifying non-stationary courses in the ripping head power consumption by recurrence plots. *Meccanica*, *45*(4), 603–608. doi:10.1007/s11012-009-9265-4

Litak, G., Syta, A., & Rusinek, R. (2011). Dynamical changes during composite milling: recurrence and multiscale entropy analysis. *The International Journal of Advanced Manufacturing Technology*, *56*(5), 445–453. doi:10.1007/s00170-011-3195-8

Maciejewski, M., Dzierżak, R., Surtel, W., & Saran, T. (2016). Human ECG indicators for fast screening and evaluation. In R. S. Romaniuk (Ed.) (1003131). Presented at the Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments, Wilga, Poland. doi:10.1117/12.2249149

Maciejewski, M., Surtel, W., & Dzida, G. (2015). Human ECG signal parameters estimation during controlled physical activity. In R. S. Romaniuk (Ed.) (96621P). Presented at the XXXVI Symposium on Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments, Wilga, Poland. doi:10.1117/12.2205811

Maciejewski, M., Surtel, W., Wójcik, W., Masiak, J., Dzida, G., & Horoch, A. (2014). Telemedical systems for home monitoring of patients with chronic conditions in rural environment. *Annals of Agricultural and Environmental Medicine*, *21*(1), 167–173.

Marras, W. S., Jorgensen, M. J., Granata, K. P., & Wiand, B. (2001). Female and male trunk geometry: size and prediction of the spine loading trunk muscles derived from MRI. *Clinical Biomechanics*, *16*(1), 38–46. doi:10.1016/S0268-0033(00)00046-2

Marwan, N., Carmenromano, M., Thiel, M., & Kurths, J. (2007). Recurrence plots for the analysis of complex systems. *Physics Reports*, *438*(5–6), 237–329. doi:10.1016/j.physrep.2006.11.001

Rangayyan, R. M., Oloumi, F., Wu, Y., & Cai, S. (2013). Fractal analysis of knee-joint vibroarthrographic signals via power spectral analysis. *Biomedical Signal Processing and Control*, *8*(1), 23–29. doi:10.1016/j.bspc.2012.05.004

Shannon, C. E. (1948). A Mathematical Theory of Communication. Reprinted with corrections from *The Bell System Technical Journal, 27*, 379–423, 623–656.

Shark, L.-K., Chen, H., & Goodacre, J. (2010). Knee Acoustic Emission: A Clue to Joint Ageing and Failure. *Rheumatology*, *49*, I79–I79.

Shark, L.-K., Chen, H., & Goodacre, J. (2011). Knee acoustic emission: A potential biomarker for quantitative assessment of joint ageing and degeneration. *Medical Engineering & Physics*, *33*(5), 534–545. doi:10.1016/j.medengphy.2010.12.009

Syta, A., Jonak, J., Jedliński, Ł., & Litak, G. (2012). Failure Diagnosis of a Gear Box by Recurrences. *Journal of Vibration and Acoustics*, *134*(4), 041006. doi:10.1115/1.4005846

Takens, F. (1981). Detecting strange attractors in turbulence. In D. Rand & L.-S. Young (Eds.), *Dynamical Systems and Turbulence, Warwick 1980* (898, pp. 366–381). Berlin, Heidelberg: Springer. doi:10.1007/BFb0091924

Tool box of recurrence plot and recurrence quantification analysis – File Exchange – MATLAB Central. (2019, March 13). Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/58246-tool-box-of-recurrence-plot-and-recurrence-quantification-analysis

Wiens, A. D., Prahalad, S., & Inan, O. T. (2016). VibroCV: A computer vision-based vibroarthrography platform with possible application to Juvenile idiopathic arthritis. *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 4431–4434). IEEE. https://doi.org/10.1109/EMBC.2016.7591710

Wu, Y., Chen, P., Luo, X., Huang, H., Liao, L., Yao, Y., Wu, M., & Rangayyan, R. M. (2016). Quantification of knee vibroarthrographic signal irregularity associated with patellofemoral joint cartilage pathology based on entropy and envelope amplitude measures. *Computer Methods and Programs in Biomedicine*, *130*, 1–12. doi:10.1016/j.cmpb.2016.03.021

Yang, H. (2011). Multiscale Recurrence Quantification Analysis of Spatial Cardiac Vectorcardiogram Signals. *IEEE Transactions on Biomedical Engineering*, *58*(2), 339–347. doi:10.1109/TBME.2010.2063704

Zubrzycki, J., Karpiński, R., & Górniak, B. (2016). Computer aided design and structural analysis of the endoprosthesis of the knee joint. *Applied Computer Science*, *12*(2), 84–95.

Applied Computer Science, vol.15, no. 1, pp. 49–61
doi:10.23743/acs-2019-04

Submitted: 2019-02-01
Revised: 2019-03-05
Accepted: 2019-03-18

work ergonomics, modeling and simulation

Damian KOLNY [0000-0003-4908-2142]*, *Dawid KURCZYK**,
Józef MATUSZEK [0000-0003-1668-6329]*

COMPUTER SUPPORT OF ERGONOMIC ANALYSIS OF WORKING CONDITIONS AT WORKSTATIONS

Abstract

The article shows issues of using computer-aided technologies for ergonomic analysis at worksplaces using a dedicated tool in the Delmia environment. The scope of the ergonomic evaluation has been limited to the analysis of RULA and NIOSH, the data needed for it was gathered on the basis of observation, interview and task analysis. The results of the research showed the strenous nature of the work, therefore improvements within undertaken workplace area were proposed and re-analyzed. The obtained results proved reduction of strenousness, which was the basis for the practical implementation of the proposed changes.

1. INTRODUCTION

Currently, the practice of many industrial plants in connection with the creation and design of work in the workplace very often involves designing the construction and functional concept of the product and the workplace itself. (Klembalska, 2006). Aspects related to ergonomics and work safety are usually taken only when the workplace has been created and is able to function.

The analysis of ergonomics and work safety can be considered from the point of view of the widely understood work environment. (Muszyński, 2016). It is possible to differentiate the factors of the material working environment and technical or organizational factors – fig.1 (Nowacka, 2010).

* University of Bielsko-Biala, Faculty of Mechanical Engineering and Computer Science, Willowa 2, 43-309 Bielsko-Biała, dkolny@ath.bielsko.pl, dkurczyk@gmail.com, jmatuszek@ath.bielsko.pl

Fig. 1. Areas of interest in work ergonomics

In the era of dynamically developing many branches of industry, constantly growing competition, efforts to reduce costs and increase productivity of workplaces, inappropriate shape of workplaces directly affects the decline in work efficiency (Lasota & Hankiewicz, 2015) and the greater number of diseases that workers can be exposed to. In the context of ergonomics, it should also be remembered that in many countries (including Poland), societies are aging constantly, which in the context of the requirements related to the compliance with EN and PN standards and health and safety regulations causes the need to improve work comfort. This condition can be achieved thanks to computer-aided tools in the processes of shaping the surroundings and equipment of workplaces (Zielińska & Kurczyk, 2011).

Among the many possible assessments of the employee's workload associated with taking different positions during the work, commonly used are observational research which do not interfere in the work process, additionally characterized by low cost and ease of use (Genaidy, Al.-Shed & Karwowski, 1994). There are many companies on the market which offers software with modules related to ergonomic analysis. In the case of conducted research, the authors used the environment of Delmia, because it is one of two (apart from Process Simulate) environments most often used by corporations to comprehensively shaping the course of the production process, taking into account ergonomic aspects as well.

2. MODELING AND WORK SIMULATION ON WORKPLACES IN DELMIA SOFTWARE

2.1. General characteristics of the software

Digital Enterprise Lean Manufacturing Interactive Application (Delmia) is a virtual platform for creating simulations in the field of design and production optimization. Specialized software enables precise mapping of objects located in the enterprise (products, processes and resources) significantly increasing the sphere of concurrency over standard CAx phases (Marconi, Germani, Favi & Raffaeli, 2018), initiating the creation of a virtual factory. It allows to (Zielińska & Kurczyk, 2011):

– selection and programming of production means,
– composing the production process,
– verification of workplaces from their ergonomics point of view.

The main advantage of this application is the ability to analyze various variants and solutions of the mentioned elements, well before the implementation phase.

Delmia is a collection of many modules that allows to design and analyze of selected areas of the product life cycle and the functioning of the company (Zielińska & Kurczyk, 2011). From a wide range of modules in Delmia, a module used for carrying out ergonomic analysis is called *"ergonomics"*.

2.2. Delmia's Ergonomics module

Simulation of manual activities and evaluation of ergonomic work in the Delmia environment is possible thanks to a dedicated Ergonomics module. It enables the analysis of manual work performed by the employee in the scope of the production tasks entrusted to him. It also provides information on potential hazards that may arise from inappropriate design or preparation of the workplace and tools. The module has a very wide range of tools that correspond to, among the others (Zielińska & Kurczyk, 2011):

– digital modeling of employees and simulation of interaction with the environment,
– visualization of the digital model of a human being, making it possible to give the employee model the desired anthropometric features (eg. sex, age, etc.)
– simulation of tasks performed by an employee using predefined movements (eg walking, lifting, postponing, etc.),
– ergonomic analysis, comprehensively assessing all elements of employee's cooperation with the work environment (implemented methods are NIOSH 81 and 91, RULA method, energy expenditure and 3D biomechanics analysis), as well as designation of the working zone based on the range of hands,
– quantitative and qualitative analysis of all aspects of the employee's attitude,
– creating dummies through a set of advanced anthropometric tools (to assess the suitability of a product or process).

Such a constructed and equipped platform facilitates proper mapping of the actual state or planned production environment, including the human-object interaction.

2.3. Selected ergonomic analyzes of the Ergonomics module

The RULA (Rapid Upper Limb Assessment) method is used for quickly assess the employee's attitude at the workplace from the ergonomics point of view (McAtamney & Corlett, 1993), especially in cases of complaints on the motor system. This method takes into account the burden on the entire musculoskeletal system, associated with the use of force, to perform a specific task, as well as the need to maintain a proper position of the body (Zielińska & Kurczyk, 2011). Analysis in this method focuses mainly on the load on the neck, trunk and upper limbs. Tests made on many groups of employees, performing work often in forced and unfavorable positions of the body, prove its credibility. In this method, each analyzed attitude is assigned a score on a scale from 1 to 7, and the interpretation of individual point values is given in Table 1.

Tab. 1. Scale and its interpretation in the RULA method

Rating	Interpretation
1–2 pts.	Acceptable attitude
3–4 pts.	The attitude should be analyzed
5–6 pts.	The attitude should be analyzed and soon changed
7 pts.	The attitude should be investigated and immediately changed

The advantages of using the RULA method are certainly the ease of execution and the short time needed to obtain reliable results. It is a very good supplement to other, more complex, ergonomic methods of workplace evaluation, especially those that assess the upper limb load at the first, preliminary stage of assessment (Zielińska & Kurczyk, 2011).

The study also uses the NIOSH equation (the National Institute for Occupational Safety and Health), which is used to assess (classify) certain hazards associated with lifting objects. The application of the updated equation in 1991 takes place mainly in the following situations (Zielińska & Kurczyk, 2011):

- estimation of two-handed risk,
- analyzing and assessing the work of many tasks with lifting,
- assessment of work associated with lifting, which may include rotation of the trunk, repeatability and duration of the task,
- determining the mass of a safe load and posing a health risk by performing a given task,
- identification of tasks posing a threat and taking steps to limit them.

Analysis of this method is a two-step process, firstly the Recommended Weight Limit (RWL) should be determined of formula 1 (Slamková, Dulina & Tabaková, 2010):

$$RWL = L_C \times H_M \times V_M \times D_M \times A_M \times F_M \times C_M \quad (1)$$

where: RWL – recommended weight limit,
L_C – load constant,
H_M – horizontal position factor,
V_M – vertical position factor,
D_M – vertical distance difference factor,
A_M – asymmetry factor,
C_M – correct workpiece handle factor.

As a result of this analysis, the recommended weight limit for a given activity is calculated. This value means the mass of the object that can be lifted by a healthy person in given conditions without the risk of damaging to health. Next step is to determine the index of lifting (formula 2), which means what multiplicity of acceptable load is the actual weight. In order to receive this value, a so-called lifting index (LI), use the following formula (Slamková, Dulina & Tabaková, 2010):

$$L_I = \frac{L}{RWL} \quad (2)$$

where: L_I – lifting index,
L – lifted weight,
RWL – recommended weight limit.

The interpretation of the obtained values is summarized in Table 2.

Tab. 2. Interpretation of results for the NIOSH equation

L_I value	Interpretation
$L_I \leq 0.5$	The risk is small, there is no need to take action.
$0.5 < L_I \leq 1$	Medium risk, risk control is needed.
$1.0 < L_I \leq 2$	The risk is high, a risk-reducing measure is needed.
$L_I > 2$	Very high risk, stop the work and take immediate action to reduce the risk.

3. EXAMPLE

3.1. The run of work on the analyzed workplace

The tests were carried out at the cutting cardboard blocks station with using a band knife attached on a band knife cutting machine. Within the discussed work-place there are: a machine, a table with a sliding top, a pallet with cardboard blocks to be cut and a pallet for covering the cut material. The operator's work consists in picking material from the pallet, transferring it and fitting it properly on the table, making a proper number of reciprocating movements (depending on the target dimensions of the fragment being cut off), and then obtaining the cut elements and placing them on the pallet below the table. Then, with use of a pallet truck, the filled pallet is put aside for transport to the next station. The outlook was visualized in Fig. 2, created on the basis of a model generated in the Delmia's environment.

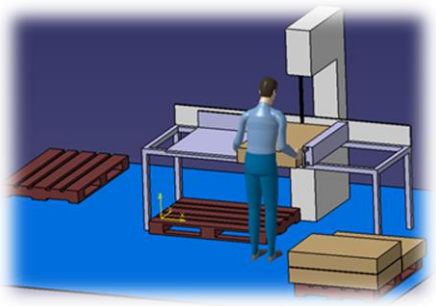


Fig. 2. Approximate arrangement of the workplace elements

The figure also shows the operator performing the material cutting operation. The cardboard block handled by the operator usually has the dimensions 800×600×150 mm and the weight is about 1.0 kg.

From the observation and the interview carried out among the operators of the analyzed workplace, it appears that the work is burdensome due to:

- standing type of work,
- bulky holding of the material during its collection,,
- fatigue resulting from repetitive movements, mainly reciprocating,
- bulky handle for feeding the table,
- additional activities related to the laying of cut elements.

According to noticed discomfort in the group being asked and specified aspects, actions were taken to carry out a virtual analysis of the ergonomic work from the ergonomics point of view.

3.2. Workplace modeling

In order to carry out ergonomic analyzes, a model of the workplace was made (fig. 3) in the Delmia Ergonomics environment, taking into account the essential elements and their parameters (height, mass, etc.) within it and the positions accepted by the operator during the performance of particular activities.

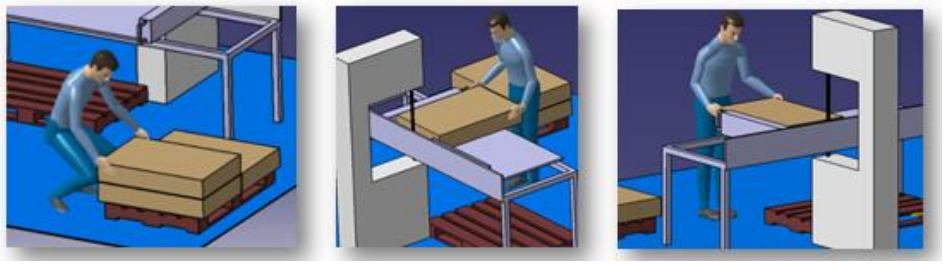


Fig. 3. Examples of the operator's position and attitude

Attitudes and positions of the employee during the work were modeled and prepared both in terms of the RULA method and the NIOSH equation (positions related to lifting). Assuming that the created model reflects the actual condition and character of the position, work was undertaken with conducting ergonomic analyzes. In fact, the model assumed some simplifications, but they did not affect the final results. Only those elements of the workplace were modeled, which are important from the point of view of the operation being performed. Elements that do not affect the work position have been omitted.

3.3. Ergonomic analysis in Delmia Ergonomics

The evaluation of the ergonomics of the operators' work at the test bench was based on the RULA method and the NIOSH equation. The following operations were taken for ergonomic analysis in the Ergonomics module:

- starting cut movement (cutting phase 1),
- ending cut movement (cutting phase 2),
- picking up material for cutting (posture A),
- fixing the material on the work table (posture B).

For all listed activities (pictured in Figure 4), the RULA analysis was carried out, while the A and B attitude was additionally analyzed by the NIOSH equation.

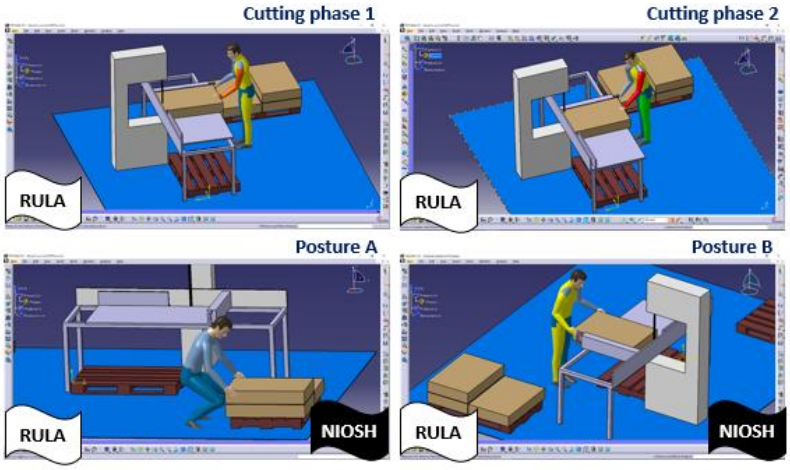


Fig. 4. Positions performed by the operator during work

RULA analysis

Having a built-in position model and selected elements for the study, the RULA analysis in the Ergonomics module was launched next. For the analysis to be carried out, the following parameters had to be additionally specified:

- the analyzed side of the body,
- the characters of the work (permanent/occasional/repeatable),
- indication of whether the arms are supported,
- an indication of whether the hands are tilted enough to cut the axis of the symmetry of the body,
- determining whether the body balance should be included.

Fig. 5 shows the result of RULA analysis showing the load state of individual body segments for the "cutting phase 1" attitude, and the overall point score of this body position is shown in Fig. 6.

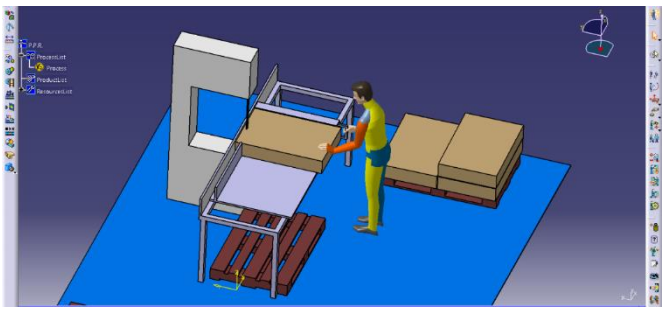


Fig. 5. Visualization of the RULA analysis for the "cutting phase 1"

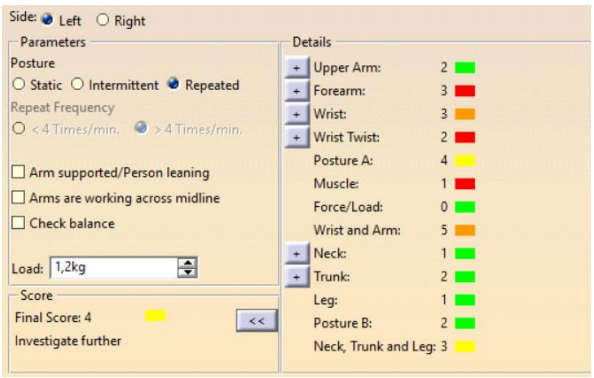


Fig. 6. Score rating of the RULA analysis for the "cutting phase 1"

From Fig. 6, it can be noticed that for such defined parameters, the final evaluation of this attitude is 4. Analogous analyzes were made for the remaining 3 postures, both for the load on the right and left side of the body. Obtaining the results is summarized in table 3. The RULA analysis takes into account the mass of material (1.2 kg, not 1.0 kg) corrected for the resistances arising on the table sliding crane, so that the operator actually manipulates a greater weight.

Tab. 3. The results of the RULA analysis

Posture assessed	The result for the left side of the body	The result for the right side of the body
Cutting phase 1	4	5
Cutting phase 1	6	4
Posture A	5	5
Posture B	4	3

According to the interpretation presented in Table 1, in the case of obtaining results with values of 5 or 6, it means the need to analyze the situation in the position more closely and make appropriate changes to reduce the overall nuisance of work in this position.

NIOSH analysis

Similarly to the RULA analysis, having such a model, it is also possible to carry out an ergonomic analysis of the NIOSH equation to examine the positions made by the worker while picking up items. To carry out this analysis it is necessary to:

- determine the frequency of activities,
- duration of activities,
- holding quality,
- the weight of the object being lifted.

As a result, an index RWL and L_I was obtained, the recommended weight limit for a analyzed activity was calculated. Figure 7 shows the visualization of the position "Posture A" (picking up) and the fragment of the result window.

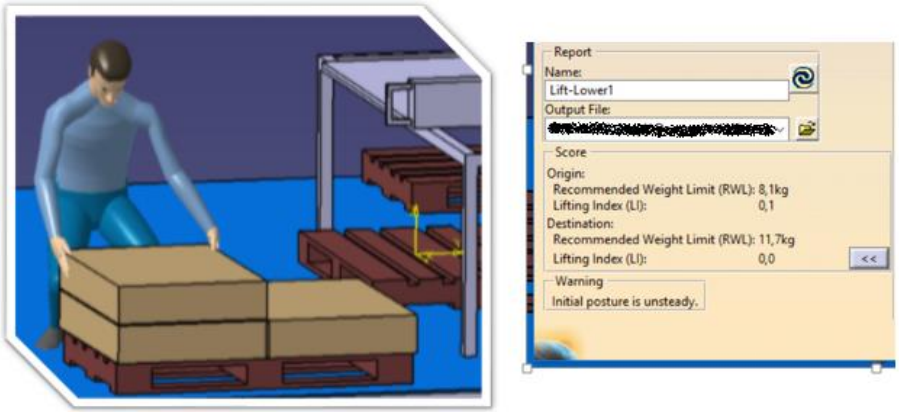


Fig. 7. Position "Posture A" and its final result

The obtained results are presented in table 4.

Tab. 4. The results of the NIOSH equation

Posture assessed	RWL	L_I
Posture A	8.1 kg	0.1
Posture B	11.7 kg	0.0

Based on these results, it can be concluded that for both attitudes there is no risk associated with lifting (L_I index less than 0.5). For posture A, the maximum weight can be up to 8.1 kg, while for posture B – 11.7 kg.

3.4. Suggestions for workplace rationalization

In connection with the alarming results obtained by RULA analysis, changes (improvements) were proposed illustrated graphically in Fig. 8.

Fig. 8. Suggestions for improvements

In order to minimize the weight manipulated by the operator, it was proposed to change the existing rail guides by linear guides. As a result, the friction that occurs, is significantly reduced, thereby reducing the supported weight.

Next, a change of the handle position was suggested in order to "force" another position assumed by the employee during the reciprocating movements. Changing the position of the handle will cause that the operator will have the strength of the whole body, pushing the table forward, and not as it was before, only by the strength of the arm, standing straight to it.

It was also proposed to reorganize the workplace in order to reduce the number of activities performed. The installation of a roll tape within the roll station, whose task will be the self-transferring of cut pieces of material to the pallet outside the cutter-table system, will not only eliminate the need to stack and export the finished pallet out, but also increase the efficiency of the station.

3.5. Modified workplace model and re-analysis

The proposed changes can almost simultaneously be introduced into the current model – without the need to interfere in the actual production environment, which can be associated with many different aspects, such as investment risk, downtime, breakdowns, etc. The effect of the proposal is presented in Figure 9.

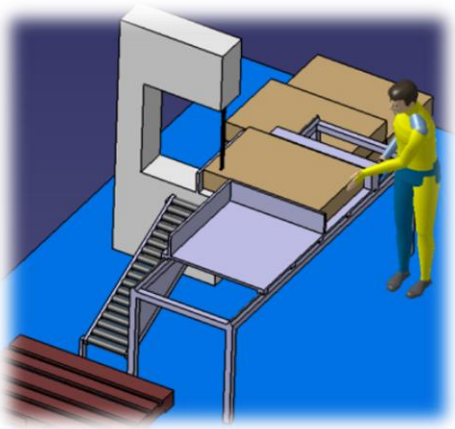


Fig. 9. Visualization of a part of modified workplace after the proposed changes

As a result of the proposed changes, the weight operated by the operator changed (reduction from 1.2 kg to 1.0 kg), the attitude assumed by the operator during the cutting process with the quality of the handle grip and the number of operations performed decreased (however, this is not taken into account in the results of ergonomic analyzes).

Similarly, RULA analysis (Table 5) and the NIOSH equation were performed for the modified position (Table 6).

Tab. 5. RULA analysis results for the modified position model

Posture assessed	The result for the left side of the body	The result for the right side of the body
Cutting phase 1	3	3
Cutting phase 1	3	3
Posture A	3	3
Posture B	3	3

Tab. 6. Analysis results of the NIOSH equation for the modified model

Posture assessed	RWL	Li
Posture A	8.3 kg	0.1
Posture B	14.2 kg	0.0

Fig. 10 presents the results obtained for RULA analysis for variants before and after making changes in the position, both for the right and left side load.

Fig. 10. Graphical presentation of results obtained using RULA analysis

4. SUMMARY

Conducted considerations and obtained results showed the correctness of the analysis in the studied area and proposing specific changes limiting the arduousness of work. Thanks to the workplace model created using the Delmia Ergonomics platform, the RULA analysis quickly obtained information on the most loaded segments of the body. It allowed to identify the main reasons for this condition

and to virtually model improvements, re-analyze and verify the effectiveness of their application. In this way, the time to undertake real activities was significantly shortened, the costs of potentially missed changes were reduced, and the whole undertaking related to the evaluation and analysis of the proposal was conducted in a non-invasive manner for the functioning of the workplace. The results of the analyzes carried out in this way may be the basic argument for implementing the proposed changes into the production.

The analysis of the NIOSH equation shows that the mass of material available to the employee is significantly lower than the permissible mass in the positions it adopts. This means that in the future, materials with a larger weight (even up to 8.3 kg) can be cut on these types of workplaces without adversely affecting the comfort of the employee's work.

Designing or simulating workplaces using the "ergonomics" module allows to evaluate them in terms of ergonomic requirements, which in the current functioning of the industry, in addition to solving current problems of work organization, create the opportunity to increase efficiency and economic benefits. The high costs of software are a common obstacle in conducting ergonomic computer analysis. For this reason, only large corporations can afford them, while in the case of smaller companies, the solution may be outsourced to external entities or academic environments.

REFERENCES

Genaidy, A. M., Al.-Shed, A. A., & Karwowski W. (1994). Postural stress analysis in industry. *Applied Ergonomics*, *25*(2), 77–87.

Klembalska, K. (2006). Modelowanie bezpieczeństwa maszyny na etapie koncepcji jako narzędzie kształtowania ergonomii i bezpieczeństwa pracy. *Journal of Research and Applications in Agricultural Engineering*, *51*(4), 21–29.

Lasota, A. M., & Hankiewicz, K. (2015). Ergonomiczna ocena pozycji przy pracy w procesie cięcia i pakowania materiałów termoizolacyjnych. *Logistyka*, *5*, 1059–1065.

Marconi, M., Germani, M., Favi, C., & Raffaeli, R. (2018). CAD feature recognition as a means to prevent ergonomics issues during manual assembly tasks. *Computer-Aided Design and Applications*. doi: 10.1080/16864360.2018.1441240

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, *24*(2), 91–99.

Muszyński, Z. (2016). Rozwój ergonomii w Polsce i na świecie. *Zeszyty Naukowe Małopolskiej Wyższej Szkoły Ekonomicznej w Tarnowie*, *29*(1), 87–100.

Nowacka, W. Ł. (2010). *Ergonomia i ergonomiczne projektowanie stanowisk pracy. Materiały dydaktyczne dla słuchaczy Studiów Podyplomowych „Bezpieczeństwo i ochrona człowieka w środowisku pracy i ergonomia"*. Warszawa: Wydawnictwo Politechniki Warszawskiej.

Slamková, E., Dulina, L., & Tabaková, M. (2010). Ergonómiwa v priemysle. Žilina: GEORG knihárstvo, tlačiareň.

Zielińska, A., & Kurczyk, D. (2011). *Wybrane narzędzie ergonomiczne w środowisku Delmia, Modele inżynierii teleinformatyki (Wybrane zastosowania)* 6 (pp. 95–106). Koszalin: Wydawnictwo Uczelniane Politechniki Koszalińskiej.

Applied Computer Science, vol. 15, no. 1, pp. 62–73
doi:10.23743/acs-2019-05

Submitted: 2018-11-28
Revised: 2018-12-13
Accepted: 2019-02-18

automatic image annotation, image tagging, metadata

Nancy WOODS [0000-0001-8396-3467]*, *Charles ROBERT**

ENCAPSULATION OF IMAGE METADATA FOR EASE OF RETRIEVAL AND MOBILITY

Abstract

Increasing proliferation of images due to multimedia capabilities of hand-held devices has resulted in loss of source information resulting from inherent mobility. These images are cumbersome to search out once stored away from their original source because they drop their descriptive data. This work, developed a model to encapsulate descriptive metadata into the Exif section of image header for effective retrieval and mobility. The resulting metadata used for retrieval purposes was mobile, searchable and non-obstructive.

1. INTRODUCTION

Today's technology centres on multimedia capabilities of hand held devices driven by the Internet and social network. According to a survey carried out by Pew Research centre in 2015, 64% of Americans own a smartphone (Smith, 2015). Other studies projected that 69.4% of global population would use mobile phone by the year 2017 (*Smartphone Users Worldwide Will Total 1.75 Billion in 2014*, 2015). It is not a surprise that cell phones are as common in South Africa and Nigeria as they are in the United States according to the statistics of a survey conducted by the Pew Research Centre in 2014 (*Pew Global*, 2016; *16 mobile market statistics you should know in 2016*, 2016). The number of Nigerians that own cell phones continues to grow yearly. The monthly subscriber statistics (Figure 1), for the Nigerian market for the period of January to March 2017, showed that 154,467,198 lines were active out of the 240,008,026 connected lines in Nigeria (*Monthly Subscriber Data*, 2016). With a population of about 190 million as at March 2017 (*World Population Review*, 2017), this means that "practically" everyone in Nigeria owns a mobile phone and this makes Nigerian

* University of Ibadan, Faculty of Science, Department of Computer Science, Oyo State, Ibadan, Nigeria, chyn_woods@yahoo.com, abc.robert@live.com

the highest mobile phone users in Africa. A report by (*Internet World Stats, Usage and population Statistics*, 2016) showed that 92.7 million Nigerians were Internet Users as at November 2015 as shown in Figure 2. The summary of the survey by (*Numbers, Facts and Trends Shaping Your World*, 2015), clearly shows that as at the time of the survey, 89% of the respondents who owned cell phones, used the cell phone firstly for sending text messages and secondly for capturing multimedia files. As the volume of these multimedia files owned by individuals continues to grow daily, with 52% of Nigerians being Internet users as at 30th September 2015 (*Internet World Stats. Usage and population Statistics*, 2016), a lot of these multimedia files are uploaded to Facebook, LinkedIn, Twitter, Instagram and other Social network sites, using their mobile devices (Strydom, 2015; Chaffey, 2016). The tendency is to get to a point where owners and users of multimedia files are 'lost' when searching for a particular file or a file that has some particular information.

	Operator	Mar '17	Feb '17	Jan '17	Dec '16
Connected Lines	*Mobile (GSM)*	235,941,553	235,532,689	234,599,704	231,601,485
	Mobile (CDMA)	3,586,095	3,586,095	3,586,095	3,586,095
	Fixed Wired/Wireless	340,895	340,566	340,465	352,045
	VoIP	139,483	126,962	116,647	59,236
	Total	240,008,026	239,586,312	238,642,911	235,598,861
Active Lines	*Mobile (GSM)*	151,999,197	153,661,547	154,660,446	154,124,602
	Mobile (CDMA)	217,566	217,566	217,566	217,566
	Fixed Wired/Wireless	152,500	151,500	151,088	154,513
	VoIP	97,935	89,871	84,447	33,099
	Total	154,467,198	154,120,484	155,113,547	154,529,780
	Teledensity	108.91	110.09	110.80	110.38

Fig. 1. NCC Mobile line Statistics January to March 2017 (*Monthly Subscriber Data*, 2017)

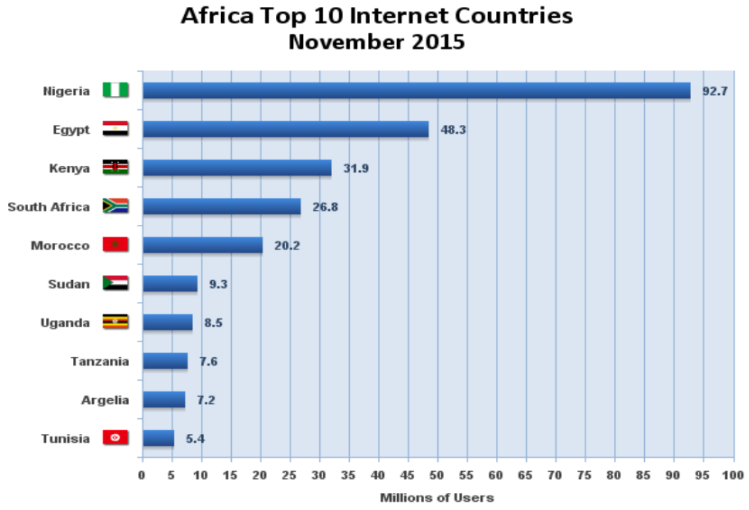


Fig 2. Africa Top 10 Internet Countries (Internet World Stats. Usage and population Statistics, 2016)

Given the volume of these images it will be cumbersome and time consuming to manually search through folders containing thousands of digital images. Some online photo development/social network companies (Facebook®, Ofoto) allow owners of photographs to manually add captions/annotations to their photos, however these captions are viewable but most often, not searchable (Kustanowitz & Shneiderman, 2005; Jaimes, 2006), because once the picture is downloaded from the Internet or the picture is removed from its source, most times it loses its caption and annotation. The loss of caption/annotation is because the annotation for such images, which were manually entered, where external to the images and were lost, as soon as the images left their source(s). A simple annotation on an image file has been reported as a method of enhancing information search (Rodden & Wood, 2003; Jaimes, 2006; Gozali, Kan & Sundaram, 2012), but the question is where such annotations are stored. The possibility of organising and 'labelling' image files can give rise to searchable multimedia data as well as enhance their usefulness (Wenyin et al., 2001; Ames & Naaman, 2007). With an all-encompassing approach, it is therefore essential that an image, if possible, should "move" with its annotation via its metadata. Image metadata are critical as they describe and manage digital images and also provide the most relevant and correct related data about that image. Metadata makes the visual content of an image easily accessible by human language terms and machine readable codes (*IPTC Photo Metadata Standard*, 2015).

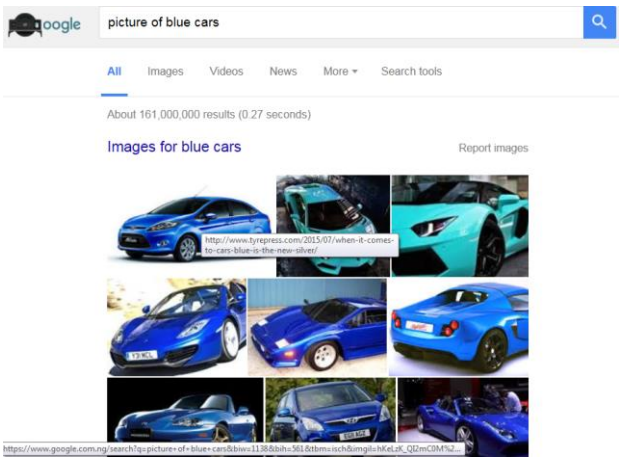


Fig 3. A snapshot of Google search with some of the results displayed (Google, 2017)

Consider Figure 3 that shows a snapshot of a Google search for "picture of blue cars"; the search fetched a number of pictures of blue cars. From the original source, it is obvious that some of the images had 'blue' appended to the filename as descriptive metadata. As soon as the picture is downloaded from the Internet it loses the 'blue' in the name, thereby losing part of its metadata.

Figure 4 shows a folder in a system where some of the images have been saved. A search on the system for "blue car" will not retrieve all the images, because the metadata for the images where external to the images and where lost, as soon as the images left their source(s). It is therefore significant that all images, if possible, "move" with some of its descriptive metadata. The aim of this work is to encapsulate descriptive metadata within an image for ease of identification, retrieval and mobility.

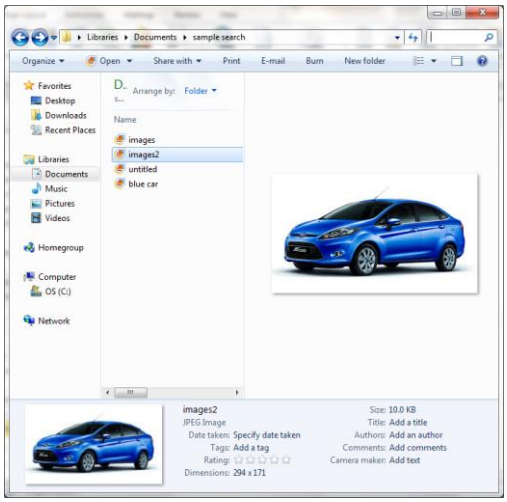


Fig 4. A snapshot of the folder containing the downloaded images from the Google search

1.1. Image Annotation

Image annotation refers to the various ways in which additional information is added to an existing image file, to give more information about the image file. Several approaches have been explored in information insertion and extraction from image files. Some of these approaches were based on imposing additional information layer on the image based on human or machine translation of these files (Kustanowitz & Shneiderman, 2005), such as the tagging of a person in a picture in Facebook. Annotation techniques can be grouped into three categories: Manual, Semi-Automated, and Automated, each with its own advantages and disadvantages (Hanbury, 2008; Zhang, Islam & Lu, 2012).

Manual annotation of image files has been shown to be the traditional method of annotating images and these annotations are usually stored in a database for ease of image retrieval, however, these annotations may not capture all the content of the image (Jeon, Lavrenko & Manmatha, 2003). Furthermore the information added depends greatly on the human annotator and his interpretation because it entails a human looking at each image and assigning the annotations as understood by him (Ivasic-Kos, Pobar & Ribaric, 2016).

The semi-automated image annotation approach starts with a manual process and then goes through annotations and extracts higher-quality, searchable meta-data, which it then re-associates with the picture. Wenyin et al. (2001) proposed a strategy for semi-automatic annotation in an image database system which depends on the user's interaction to provide an initial query and feedback and the system's capability for using these annotations as well as image features in retrieval to annotate the images in the database. In other to retrieve images using text, the images must be labelled or described in the surrounding text and since manual or semi-automatic method for providing image annotation can be a tedious and expensive task, especially when dealing with a large number of images, automatic image annotation has appeared as a solution (Ivasic-Kos, Pobar & Ribaric, 2016).

The goal of automatic image annotation, given an input image, is to assign a few relevant text keywords to that image which reflects its visual content (Makadia, Pavlovic & Kumar, 2008), while utilising the images' content to assign a richer, more relevant set of keywords. Automatic annotation of images was done within the digital camera as at the time the image was captured, by applying the date, time and GPS stamps, with date and time being the most common (Kustanowitz & Shneiderman, 2005). This approach embedded these technical annotation in the image but did not add any text that could describe the content of the image itself.

Some region-based approaches to automatic annotation by (Lavrenko, Manmatha & Jeon, 2003; Feng & Lapata, 2008; Weston, Bengio & Usunier, 2010) associated words with image regions. More specifically, they assumed that an image is segmented into regions and that image features were computed over each of these regions. Therefore, given a set of training images with annotations, probabilistic models allowed them to predict the probability of generating a word given the features computed over different regions in an image and then use the outcome for automatic image annotation of any new image.

However, one of the first approaches towards automatic image annotation proposed by (Mori, Takahashi & Oka, 1999), was the co-occurrence model that was based on the global features of an image. The annotation approach collected co-occurrence counts between keywords used for image annotation as well as image features and used these keywords to predict annotations for new images. (Duygulu, Barnard, Freitas & Forsyth, 2002) modified this approach by treating image regions and keywords as a bi-text to construct an image region-word dictionary. They represented images by a group of blobs (related region), and then translated the blobs into a set of keywords. These keywords were then used to annotate a new image. A snapshot of their result is presented in Figure 5 which shows the various 'blobs' and the keyword assigned to them.

Fig. 5. A snapshot of the result from Duygulu *et al.* (Duygulu et al., 2002)

(Wang, Zhang, Jing & Ma, 2006) proposed a global-feature based approach which searched for semantically and visually similar images on the Web, mined annotations from their descriptions and then assigned them to a query image. A key idea behind these approaches is to find the images most similar to the test or query image and then use their shared keywords for annotation. In an alternative global approach, (Makadia, Pavlovic & Kumar, 2008) proposed baseline methods for image annotation which are built on the assumption that images similar in appearance are likely to be annotated with similar sets of keywords, therefore they treated image annotation as a process of transferring keywords to an image from its nearest neighbours.

More recently, (Kuric & Bielikovan, 2015) proposed a method that combined global and local features in the process of automatic image annotation, to retrieve the best results during a search. The combination was more suitable to represent complex scenes and events categories because global and local features provide different kinds of information. The segmentation process, which was called "keypoint extraction" is closely related to edge detection. The goal was to obtain annotation for extracted segments of the target image and to estimate probability for each annotation.

Most of the approaches presented assigned annotations that either obstruct the view of the image or store these annotations as indexes outside the image, such that if the image left its source, it may need to be re-annotated. Hence, the importance of letting an image 'move' with its annotation. The approach proposed and implemented in this research work was to encapsulate image annotation (descriptive data) / metadata within the image, such that the information is non-obstructive, searchable and most importantly 'mobile'. To achieve this, the high level feature of JPEG image files especially the user text tags will be updated with descriptive text which portrays some of the actual content of the file.

2. METHODOLOGY

To ensure that there is no disconnect between descriptive data of a digital image and the digital image itself, the National Information Standards Organisation (NISO) developed several principles for encoding important descriptive metadata directly in the digital image files themselves alongside the several technical metadata that are usually stored as at the time of capture of these digital images (National Information Standards Organization, 2004, 2015). This would create a digital image file that is really self-describing because such images would store additional details (metadata) within itself and move about with such details. There are several standards that guide the capture and creation of image metadata, some of which are International Press Telecommunications Council (IPTC) Information Interchange Model (IIM), Extensible Metadata Platform (XMP) (*Extensible Metadata Platform (XMP)*, 2014) and Exchangeable Image File Format (EXIF). For the purpose of this research work, the EXIF standard was adhered to.

2.1. Exchangeable Image File Format (EXIF)

The EXIF standard was created by the Japan Electronics and Information Technology Industries Association (JEITA) to standardise the way digital/electronic devices that can be used to capture digital image, format and record image metadata at the time of the image capture (Japan Electronics and Information Technology Industries Association, 2002). Since its establishment, the EXIF standard has become the regular standard for formatting and storing digital image metadata therefore, this format is found on almost all digital imaging devices. Consequently, EXIF is typically used to store technical metadata such as the name of camera used for image capture, where obtainable, the camera settings used, the exact time and date of image capture, image size, among other technical metadata. In summary, EXIF specification specifies the guidelines that should be followed when recording image metadata in files. It also specifies the structure of digital image files, the user tags allowable and their management (Japan Electronics and Information Technology Industries Association, 2002). Digital Image formats such as JPEG and TIFF have segments in their header section, reserved for storing the image metadata.

2.2. Encapsulation steps

To achieve a more useful image file, this research work, encapsulated image descriptive metadata in the header section of a supplied image by modifying the author, title, keywords, and comment tags sections in the image header. Figure 6 shows the simple flow-model used to encapsulate metadata in JPEG files. The flow-model uses the descriptive metadata that were recognised using the steps proposed by (Woods, 2017). These metadata were stored in a text file with definitive delimiters that separate the four tags to be updated.

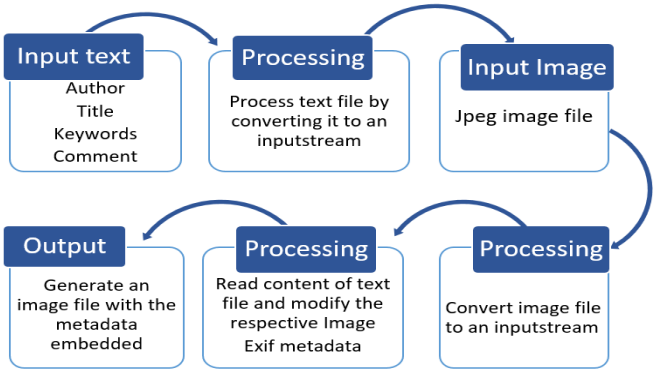


Fig. 6. Steps for metadata encapsulation

From figure 6 we note that firstly, the text file containing the intended metadata for a JPEG file is loaded. A sample of the content of this file is shown in Figure 7. The metadata are delimited by '&&' and are for updating four different segments in the Exif section of the image file. The first delimited string is intended to be used to update the **AUTHOR** tag; this is followed by the string for the **TITLE** tag, then the string for the **KEYWORDS** tags, and lastly the string for the **COMMENT** tag. The content of this text file is processed to extract the 4 strings for the different sections of the Exif tags by temporarily storing the extracted strings in four different variables.

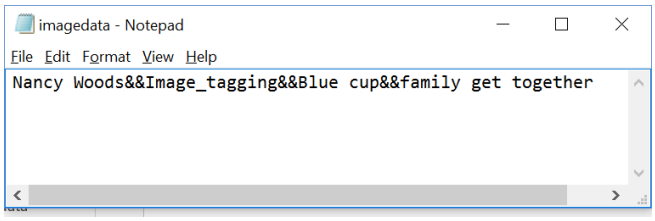


Fig. 7. Sample text file

Next, the JPEG image file that has the metadata is then loaded, converted to an inputstream and then the EXIF tags are examined. The examination is necessary because it checks if the concerned tags already have text content as well as the value stored in them. None of the digital images used in this work contained any meaning data. So basically the JPEG file is processed as follows:

1. Get all the metadata properties that are currently in the EXIF directory.
2. Create the author, title, keywords, comment tags with the data from the text file.
3. Write the new tags into the EXIF directory and the root directory of the jpeg metadata.

Once the content of the EXIF directory are modified, the file is saved. The results of these steps are discussed in the next section of the paper

3. RESULTS

Available descriptive metadata were automatically embedded into the EXIF section of digital image header of selected natural JPEG images from an image dataset. The resulting metadata which can always be extracted and used for retrieval purposes was made mobile, searchable and non-obstructive. The results of the process can only be viewed when the metadata of the file is extracted and displayed or stored elsewhere, since the metadata is encapsulated within the header section of the image file.

Figure 8 shows the extracted and displayed metadata field for an input file "birthday pix 076.jpg". This Figure shows a snapshot of some of the EXIF properties of "birthday pix 076.jpeg" before it was modified and updated. It can be seen from the snapshot that the following fields XPAuthor, XPTitle, XPComment and XPKeywords have no values in them. The output shows "Not found" for these fields. The only field with a value is the XPKeywords field, unfortunately, the values are meaningless and incomprehensible.

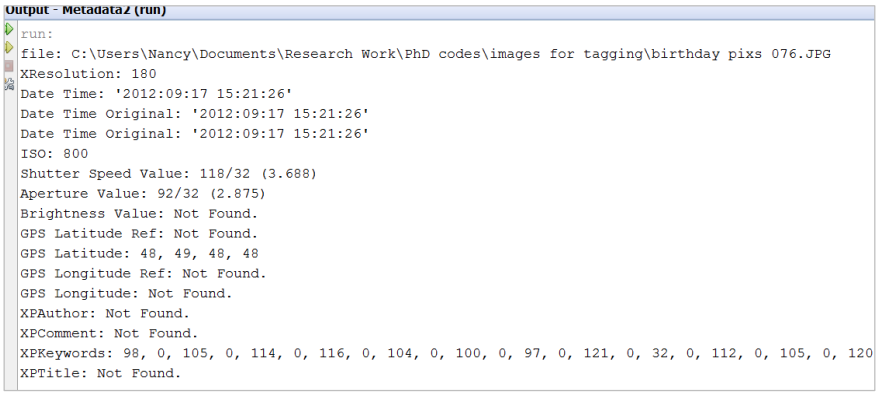


Fig. 8. EXIF properties before modification

After modification, these fields were updated with values taken from the text file. The result is displayed in Figure 9. Figure 9 shows the result of updating some of the EXIF properties of "birthday pix 076.jpeg". The screenshot shows the enriched metadata properties of the file with the following fields updated with descriptive metadata: XPAuthor, XPTitle, XPComment and XPKeywords. The original image was enriched with the descriptive metadata making it possible to extract and search the fields while ensuring that the actual visual contents of the image have not been obstructed by the 'tags'.

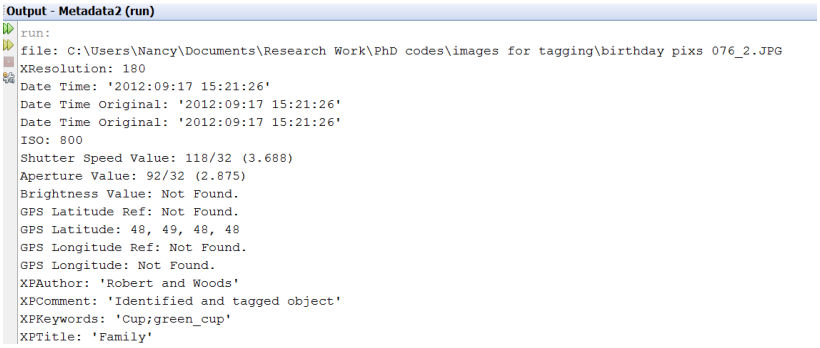


Fig. 9. EXIF properties after the modification

4. DISCUSSIONS

The embedded metadata are non-obstructive in the sense that they do not obstruct any portion of the image itself as against the result displayed in Figure 5. The metadata is also mobile, because it is embedded within the header section of the image and therefore, moves with the image. This is better that the approach where the annotation or tag is external to the image and may be lost if that image is removed from it source.

Since the technology and communication of today, centres on multimedia capabilities of mobile phones and handheld devices driven by the Internet and social network, which has increased the rate with which digital images are acquired and stored by both organisations and individuals. Consequently businesses and persons have created huge collections of digital images that have become cumbersome to explicitly identify and retrieve due to several reasons. Some of which are change in identity of an image once the image is accessed and saved away from its original source, manipulations and modifying of images by other individual apart from the owners and sometimes the inability to correctly qualify images. These can make subsequent retrieval of the image demanding. Identification, qualification and subsequent retrieval of digital images have been generally achieved with processes such edge detection, manual and visual identification of digital images by humans as well as manual annotation of digital images. These processes are either cumbersome, time consuming.

By automatically embedding descriptive data called metadata in the Exif portion within the jpeg image header, will make such metadata mobile and searchable. Mobility in the sense that even if the image left its source, it moved with its descriptive data which can be easily identified and read for image retrieval purposes. The embedded metadata was un-obstructive and mobile. This means that even if such images left their original source, they moved with their descriptive metadata. This makes the images easier and faster to retrieve and reduces human error.

REFERENCES

16 mobile market statistics you should know in 2016. (2016, August 22). In *Afilias Technologies Ltd*. Retrieved from Device Atlas: https://deviceatlas.com/blog/16-mobile-market-statistics-you-should-know-2016

Ames, M., & Naaman, M. (2007). Why We Tag: Motivations for Annotation in Mobile and Online Media. *CHI 2007, Tags, Tagging & Notetaking* (pp. 971-980). California: ACM. doi:10.1145/1240624.1240772

Chaffey, D. (2016). Global social media research summary 2016. Retrieved August 22, 2016, from Smart Insights: http://www.smartinsights.com/social-media-marketing/social-media-strategy/new-global-social-media-research/

Duygulu, P., Barnard, K., Freitas, N., & Forsyth, D. (2002). Object Recognition as Machine Translation: Learning a Lexicon for a Fixed Image Vocabulary. *The 7th European Conference on Computer Vision* (pp. 97–112). Copenhagen.

Extensible Metadata Platform (XMP). (2014, January 8). In *Adobe Systems Incorporated*. Retrieved from Adobe Systems Incorporated Web site: http://www.adobe.com/products/xmp.html

Feng, Y., & Lapata, M. (2008). Automatic Image Annotation Using Auxiliary Text Information. *Association for Computational Linguistics -08* (pp. 272–280). Columbus: Association for Computational Linguistics.

Gozali, J. P., Kan, M.-Y., & Sundaram, H. (2012). How do people organize their photos in each event and how does it affect storytelling, searching and interpretation tasks? *Proceedings of the 12th ACM/IEEE-CS joint conference on Digital Libraries* (pp. 315–324). Washington, DC: ACM New York. doi:10.1145/2232817.2232875

Hanbury, A. (2008). A survey of methods for image annotation. *Journal of Visual Languages & Computing*, *19*(5), 617–627. doi:10.1016/j.jvlc.2008.01.002

Internet World Stats. Usage and population Statistics. (2016, August 22). In *Internet World Stats.* Retrieved from Internet World Stats: http://www.internetworldstats.com/stats1.htm

IPTC Photo Metadata Standard. (2016, January 22). In *International Press Telecommunications Council*. Retrieved from International Press Telecommunications Council Website: https://iptc.org/standards/photo-metadata/iptc-standard

Ivasic-Kos, M., Pobar, M., & Ribaric, S. (2016). Two-tier image annotation model based on a multi-label classifier and fuzzy-knowledge representation scheme. *Pattern Recognition*, *52*, 287–305. doi:10.1016/j.patcog.2015.10.017

Jaimes, A. (2006). *Human Factors in Automatic Image Retrieval System Design and Evaluation*. Proceedings of SPIE Vol. #6061, Internet Imaging VII. San Jose, CA, USA. doi:10.1117/12.660255

Japan Electronics and Information Technology Industries Association. (2002*). Exchangeable image file format for digital still cameras: Exif Version 2.3.* Japan: Japan Electronics and Information Technology Industries Association.

Jeon, J., Lavrenko, V., & Manmatha, R. (2003). *Automatic Image Annotation and Retrieval using Cross-Media Relevance Models*. SIGIR'03. Toronto: ACM. doi:10.1145/860435.860459

Kuric, E., & Bielikovan, M. (2015). ANNOR: Efficient image annotation based on combining local and global features. *Computers & Graphics*, *47*, 1–15. doi:10.1016/j.cag.2014.09.035

Kustanowitz, J., & Shneiderman, B. (2005). *Motivating Annotation for Personal Digital Photo Libraries: Lowering Barriers While Raising Incentives.* Tech. Report HCIL–2004–18. University of Marlyand.

Lavrenko, V., Manmatha, R., & Jeon, J. (2003). A model for learning the semantics of pictures. *The 16th Conference on Advances in Neural Information Processing Systems.* Vancouver.

Makadia, A., Pavlovic, V., & Kumar, S. (2008). A New Baseline for Image Annotation. In T. P. Forsyth D. (Ed.), *ECCV '08 Proceedings of the 10th European Conference on Computer Vision: Part III* (pp. 316–329). Berlin, Heidelberg: Springer. doi:0.1.1.145.9205

Monthly Subscriber Data. (2017, August 22). In *The Nigerian Communications Commission*. Retrieved from NCC Subscriber Statistics: http://ncc.gov.ng/index.php?option=com_content&view=article&id=125:subscriber-statistics&catid=65:industry-information&Itemid=73

Mori, Y., Takahashi, H., & Oka, R. (1999). Image-to-word transformation based on dividing and vector quantizing images with words. *Proceedings of the 1st International Workshop on Multimedia Intelligent Storage and Retrieval Management*. Orlando. doi:10.1.1.31.1704

National Information Standards Organization. (2004). *Understanding Metadata. Bethesda, USA: NISO Press.*

National Information Standards Organization. (2015). *RLG Technical Metadata for Images Workshop Report*. Retrieved from National Information Standards Organization: http://www.niso.org/imagerpt.html

Numbers, Facts and Trends Shaping Your World. (2015, July 20). In *Pew Research Centre.* Retrieved from http://www.pewresearch.org

Pew Global. (2016, August 22). In *Pew Research Center*. Retrieved from Pew Research Center, Global Attitudes & Trends: http://www.pewglobal.org/2015/04/15/cell-phones-in-africa-communication-lifeline

Rodden, K., & Wood, K. R. (2003). How Do People Manage Their Digital Photographs? *SIGCHI Conference on Human Factors in Computing Systems* (pp. 409–416). Florida: ACM New York. doi:10.1145/642611.642682

Smartphone Users Worldwide Will Total 1.75 Billion in 2014. (2015, July 20). In *eMarketer.* Retrieved from http://www.emarketer.com/Article/Smartphone-Users-Worldwide-Will-Total-175-Billion-2014/1010536

Smith, A. (2015). US smartphone use in 2015. Retrieved July 20, 2015, from Pew Research Centre: http://www.pewinternet.org/2015/04/01/us-smartphone-use-in-2015/

Strydom, T. (2015). Facebook rakes in users in Nigeria and Kenya, eyes rest of Africa. Retrieved August 22, 2016, from Reuters: http://www.reuters.com/article/us-facebook-africa-idUSKCN0RA17L20150910

Wang, X.-J., Zhang, L., Jing, F., & Ma, W.–Y. (2006). AnnoSearch: Image Auto-Annotation by Search. *The 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*. IEEE. doi:10.1109/CVPR.2006.58

Wenyin, L., Dumais, S., Sun, Y., Zhang, H., Czerwinski, M., & Field, B. (2001). Semi-Automatic Image Annotation. INTERACT '01: IFIP TC13 International Conference on Human-Computer Interaction (pp. 326–333). IOS Press.

Weston, J., Bengio, S., & Usunier, N. (2010). Large scale image annotation: learning to rank with joint word-image embeddings. *Machine Learning*, *81*, 21–35. doi:10.1007/s10994-010-5198-3

Woods, N. C. (2017). *Low-level Multimedia Recognition and Classification for Intelligence and Forensic Analysis*. Unpublished Thesis.

World Population Review. (2017, October 3). In *World Population Review*. Retrieved from http://worldpopulationreview.com/countries/nigeria-population

Zhang, D., Islam, M. M., & Lu, G. (2012). A review on automatic image annotation techniques. *Pattern Recognition*, *45*(1), 346–362. doi:10.1016/j.patcog.2011.05.013

Applied Computer Science, vol. 15, no. 1, pp. 74–83
doi:10.23743/acs-2019-06

Submitted: 2018-09-26
Revised: 2018-10-07
Accepted: 2019-01-20

programming, LabView, polymers, printing 3D

Sylwester KORGA [0000-0002-1327-0320]*,
Marcin BARSZCZ [0000-0002-9061-4414]*,
Krzysztof DZIEDZIC [0000-0003-4909-9980]*

DEVELOPMENT OF SOFTWARE FOR IDENTIFICATION OF FILAMENTS USED IN 3D PRINTING TECHNOLOGY

Abstract

The aim of the work was to develop a computer program that allows identification of polymer materials that are used in 3D printing technology. The computer program was made using the algorithm that concerns the method of thermal polymer degradation. Filament samples were prepared for this purpose and then set on fire. The collected data on the flammability of polymers was used in an algorithm that can make a decision to identify the name of the polymer. The software can be used to identify polymer prints used for 3D printing technology. The computer program supports the process of recycling plastics and supports ecological work.

1. INTRODUCTION

At present, plastics belong to one of the most popular construction materials. Their mechanical, physical and chemical properties make it possible to use polymers in many industrial sectors. Over the last years, there has been a large increase in the production of plastics materials, which is associated with their increased use, causing the displacement of other production materials (Klepka, 2014; Wittbrodt, Glover, Laureto, Anzalone, Oppliger, Irwin & Pearce, 2013).

Thanks to its numerous advantages, such as the ease of forming products with complex shapes, chemical resistance and high mechanical strength in relation to low density, plastics have found application in additive printing technology (Garbacz & Dulebova, 2013).

* Lublin University of Technology, The Faculty of Electrical Engineering and Computer Science, Nadbystrzycka 38A, 20-618 Lublin, Poland, +48 81 538 42 87, s.korga@pollub.pl, m.barszcz@pollub.pl, k.dziedzic@pollub.pl

Low production costs of input production materials and ease of access to polymer filaments led to the development of 3D printing technology (Pearce et al., 2010).

3D printing is carried out by applying a thermoplastic material pressed through the nozzle. The nozzle is heated to the plasticizing temperature of the given material. The material flow is limited by a nozzle that moves automatically. In this way, the model is produced layer by layer. The requirement to obtain an acceptable product is to choose the right polymer filament and technological parameters that apply to it (Garbarczyk, Józefowic & Rybarczyk, 2014). Identification of the polymeric material is important not only due to the selection of material for the production of the product, but also due to its identification in the recycling process (Błędzki & Kardasz, 1998). Therefore, an attempt was made to develop software for the identification of filaments used in 3D printing technology (Korga & Flis, 2018).

2. PROBLEMATICS ON POLYMER FILAMENT IDENTIFICATION

There are many methods to identify polymers, but they are mainly expensive laboratory methods. Therefore, one of the most popular methods for identifying polymers is the use of recycling marks (Broniewski, Kapko & Płaczek, 2000). This method was introduced by the Ministry of the Environment in accordance with art. 17 section 2 of June 27, 1997 on waste. Markings of polymer products using recyclable marks enabled the development of the so-called Material recycling. It is a process that uses polymer waste instead of input polymers to produce materials. This type of recycling allows you to reduce the consumption of oil, emissions of harmful compounds for the environment and energy consumption. The disadvantages of the process are psychological barriers, public opinion, quality of processed plastics, ecology and gas emissions (Okamoto, 2003; Mroziński, 2010). Unfortunately, in most cases, products obtained using 3D printing technology are not marked with recycling marks, which makes their identification difficult. The problem of identifying filaments and polymer prints can be solved by using the thermal decomposition method. It consists in observing changes in chemical properties of the polymer as a result of providing an elevated temperature value for the analyzed polymer (Błędzki & Faruk, 2006; Wróblewska-Krepsztul, Michalska–Pożoga, Szczepiński & Szczepiński, 2017).

The use of the thermal decomposition method of polymers gives the possibility of sorting and segregating which results in obtaining more materials that can be recycled. The complexity of the thermal decomposition process of polymers causes some difficulties regarding the analysis of many observed factors. The use of computer aided systems may be a great facilitation of the decision making process regarding the identification of a polymer (Rosato, Rosato & Schott, 2010).

3. POLYMER IDENTIFICATION USING THE THERMAL CUTTING METHOD

Before starting the process of burning polymers, the samples were collected on the basis of markings placed on them by the manufacturer. Analyzing the current scientific and research work and review of available literature dealing with the subject of polymer identification, they were identified and then cleaned and subjected to fire tests (Przygodzki, Włochowicz & Janowska, 2007).

Tab. 1. Identification of polymers based on thermal decomposition of the sample

The name of the filament	View of prepared filament samples	The initial temperature of the sample [°C]
Ultra PET		20
PETG		20
PLA		20
ABS		20
Rubber		20

The sample was placed in the holders, keeping it in the flame of the burner until it was ignited. The sample was slowly heated to observe all occurring phenomena. During the test, characteristic features of the burning sample were recorded, for example: the color of the flame, the smell of smoke, the ease of smoking and the self-extinguishing process.

3.1. Preparation and characterization of samples on the form polimer filaments

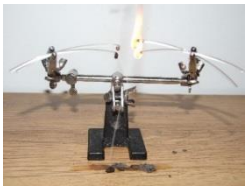
In order to carry out the research process, a set of polymer samples in the form of a filament was prepared. All prepared samples were produced by one manufacturer – Spectrum Premium 3D Filaments. The samples were taken from the manufacturer's hermetically sealed packaging, therefore no purification process was carried out. Samples prepared for testing have the same length and diameter. A set of filament samples is shown in Table No. 1.

3.2. Thermal decomposition processes of polymeric filaments

The research process using the thermal polymer decomposition method was carried out on previously prepared samples. A butane burner was used to trigger the filament burning process. The combustion of samples took place in the environment. The flame temperature of the burner was 1150 °C. The view of burned filament samples is shown in table 2.

On the basis of observations of the combustion process of samples, information on the behavior of the polymeric material in the flame environment was collected. The collected data was used to build the algorithm of the program enabling the decision-making processes concerning the identification of polymeric materials.

Tab. 2. Identification of polymers based on thermal decomposition of the sample

The name of the filament	View of filament samples subjected to a fire test	Flame temperature (gas burner – butane) [°C]
Ultra PET		1150
PETG		1150
PLA		1150
ABS		1150
Rubber		1150

4. DEVELOPMENT OF THE PROGRAM FOR POLYMER PLANT IDENTIFICATION

The repeatability of the occurrence of flammability characteristics, which are found in the literature as tabular data, makes it difficult to identify the polymer with the highest probability. Therefore, an attempt should be made to develop software that would allow the identification of polymers in the analysis of similar material properties of incinerated polymers (Rabek, 2013).

This type of software analyzing the flammability characteristics allows to determine the material from which the filament or product was made (Matuana, Park & Balatinecz, 1998). Identyfications of the material has shown in the table 3.

Tab. 3. Identification of polymers based on thermal decomposition of the sample

Type of material	Behavior of the material after smoking in a flame	Look and the color of the flame	Odor/smoke	Plastic changes during heating
ULTRA PET (Polyethylene terephthalate)	After burning, it burns further	Steming, yellow with a blue center, drips with burning drops	Similar to the smell of burned paraffin	It melts very easily, loses its turbidity, is neutral
PETG (polyethylene terephthalate with admixture of glycol)	After burning, it burns further	It does not burn and it does not choke	The smell of vinegar	Decomposition at low melting temperatures
PLA (Polilaktyd)	After igniting, it goes out	Low flammability – goes out	Similar to the smell of burned paraffin	It does not emit smoke
ABS (Acryl-nitrile-butadiene-styrene)	After igniting, it goes out	Flame bright, low flammability, dripping drops	Sweet aroma	It does not emit smoke
Spectrum Rubber (elastomer Rubber)	After burning, it burns further	Yellow flame, black charring of the material	Smell strangling	Smoke

4.1. Develompment of an algorithm for the identification of polimer materials

In order to identify polymers based on fire tests, proprietary software was created on the basis of table No. 3. The user of the program, having information about the behavior of the polymer during its combustion, selects material features from four drop-down lists. Material characteristics of the material burned were divided into four main groups:

- material behavior after the heating process,,
- the appearance and color of the flame,
- smell of fumes,
- plastic deformation during heating.

The number has been assigned to each polymers feature from a given group. The zero position of each group refers to the polymer with the number zero. Each item of the first of the four groups concerns the first polymer, etc. By selecting material features, the user determines the selected item from the four lists. Selected values are passed to the one-dimensional matrix. Each cell in the matrix was assigned a space for the value from the corresponding list. Data from the matrix are calculated using the statistical fashion function. The answer of the function is the numerical value most often found in the matrix. This value is sent to the Case structure selector. Particular cases of this structure were assigned polymer materials according to the numbering found in the four lists. The Case selector invokes the display of the identified polymer in this way. The scheme of the program's algorithm is shown in Figure 1.

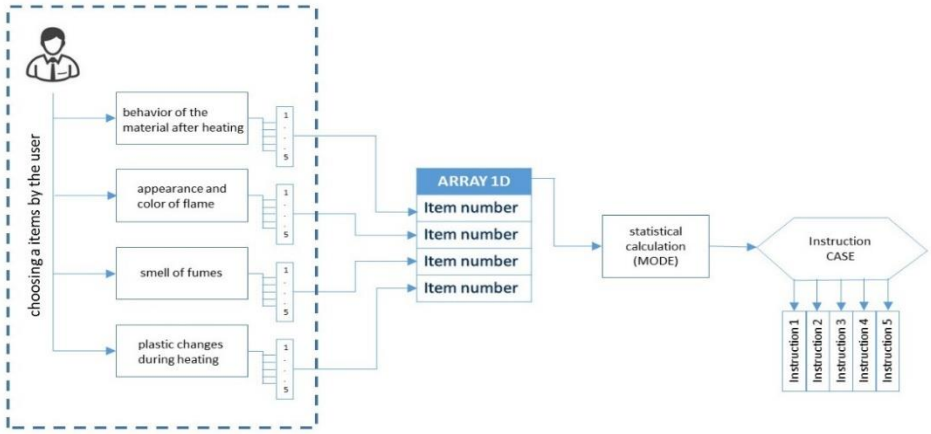


Fig. 1. Algorithm of the program for identification of polymer materials

The developed algorithm was used to build a program for identifying filaments used in 3D printing technology.

4.2. Developing the program using the algorithm

The LabView programming environment was used to build the program. It is an integrated environment intended for both software development as well as for controlling control and measurement systems as well as data processing and analysis. The language of programming in the LabView environment is G. On the basis of the developed algorithm, a program for identifying polymer materials has been made (Targowski, Sylwestrzak & Bajraszewski, 2009).

The view of the program's block diagram is shown in Fig. 2. The front panel view is shown in Figure 3.

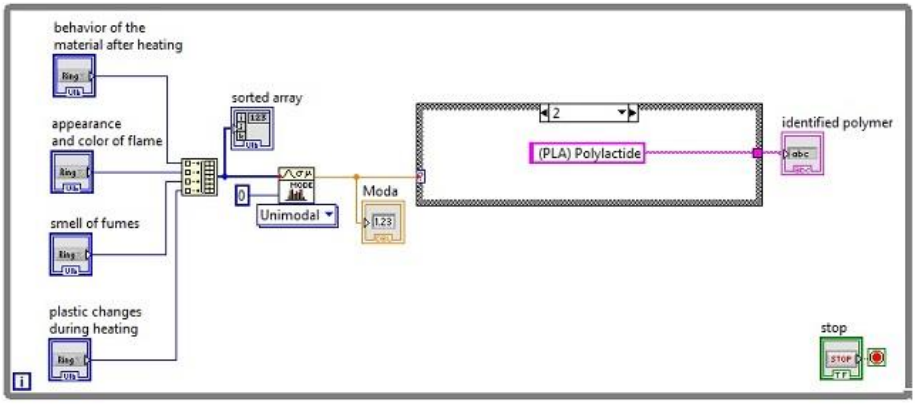


Fig. 2. Program view in block-diagram form

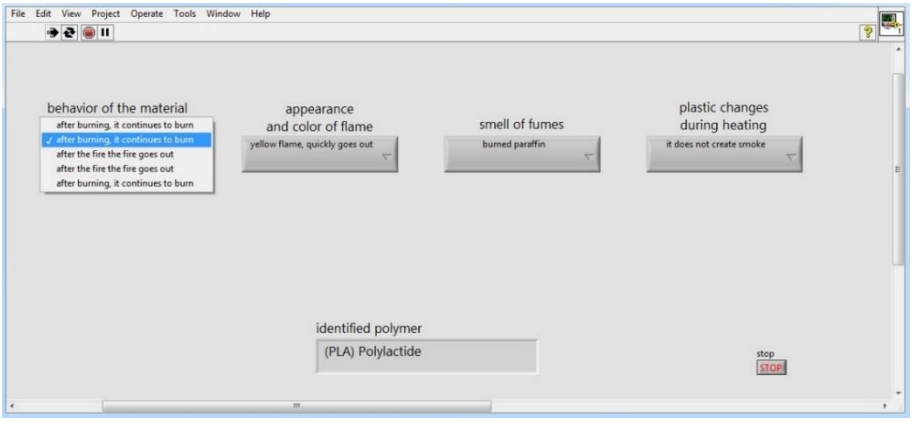


Fig. 3. Program view in the form of a user panel

Figure number 3 shows the main program window view on the example of selecting one of the polylactide polymers. After observing the features during the fire test of the polymer, the user selects the appropriate options from the program drop-down list. The computer program uses the input data and case construction to identify the polymer. The user obtains information about the name of the polymer being burned. The software enables the identification of five filaments on the polymer market. Taking into account the continuous development of the present and the emergence of new polymer materials, it is recommended to expand the program with further material items.

5. CONCLUSIONS

The tests of combustion of polymeric materials allowed organoleptic observation of characteristic features. The performed fire tests of polymers were described on the basis of a literature review and own research. On this basis, five most-used filaments in 3D printing technology were described. The National Instruments LabView environment was used to make the software used to identify polymers. In order to check the correctness of the LabView program, attempts were made to work in various combinations.

Using the results of the research, the following conclusions were determined:

- Polymers that contain additives to reduce or delay the flammability of plastics (flame retardants) inhibit the ignition process and reduce the rate of pyrolysis reactions. The rate of combustion of the polymer is determined subjectively and it is difficult to establish it in a computer program.
- Additional substances added to polymers, e.g. fillers, plasticizers, dyes, stabilizers, lubricants, can change the behavior of the polymer during combustion. Then using the program is difficult.
- During the combustion test of polymers, it was observed that some of them did not sustain smoking after removing them from the flame. And this behavior makes the filament identification process more difficult.
- Some filaments have the ability to self-burn after removing the samples from the flame. This type of information can be included in a computer program to identify flammable 3D prints.

The yellow flame is a characteristic feature of polymers that release aromatic hydrocarbons during burning. On the other hand, aliphatic hydrocarbons burn with a blue flame, giving off an unnoticeable, burning flame, or they do not emit a burning flame at all.

The collected information from the research process was used to identify polymers using the proprietary program. From the validation process of the program, it follows that the program identified all of them correctly for the five studied filaments. Therefore, you can infer about the correct execution of the algorithm and the operation of the program. The authors decided to use the five most common filaments on the market. However, the structure of the program gives the possibility of expanding its functionality to identify further polymeric materials.

REFERENCES

Błędzki, A. K., & Faruk, O. (2006). Influence of Processing Temperature on Microcellular Injection-Moulded Wood-Polypropylene Composites. *Macromolecular Materials and Engineering*, *291*(10), 1226–1232.

Błędzki, A. K., & Kardasz, D. (1998). Możliwości szybkiej identyfikacji tworzyw sztucznych w procesie recykling. *Polimery*, *43*(2), 79–87.

Broniewski, T., Kapko, J., & Płaczek, J. (2000). *Metody badań i ocena właściwości tworzyw sztucznych*. Warszawa: WNT.

Garbacz, T., & Dulebova, L. (2013). Porophors during the extrusion process. *Chemistry and Chemical Technology*, *7*(1), 113–118. doi:10.23939/chcht07.01.113

Garbarczyk, E., Józefowic, K., & Rybarczyk, A. (2014). Technologia druku 3d na zajęciach laboratoryjnych. *Poznan University of Technology Academic Journals. Electrical Engineering*, *80*, 245–251.

Okamoto, K. T. (2003). *Microcellular Processing*. Cincinnati: Hanser Gardner Inc.

Klepka, T. (2014). *Nowoczesne materiały polimerowe i ich przetwórstwo*. *Część 1*. Lublin: Wydawnictwo Politechniki Lubelskiej.

Korga, S., & Flis, M. (2018). Analiza najczęstszych niepowodzeń występujących podczas procesu druku addytywnego. In B. Buraczyńska & A. Kuczmaszewska (Eds.), *Młody inżynier XXI wieku* (pp. 35–45). Lublin: Wydawnictwo Politechniki Lubelskiej.

Matuana, L. M., Park, C. B., & Balatinecz, J. J. (1998). Structures and mechanical properties of microcellular foamed polyvinyl chloride. *Cellular Polymers*, *17*(1), 1–16.

Mroziński, A. (2010). Problemy recyklingu tworzyw polimerowych. *Inżynieria i Aparatura Chemiczna*, *49*(5), 89–90.

Pearce, J. M., Morris Blair, C., Laciak, K. J., Andrews, R, Nosrat, A., & Zelenika-Zovko, I. (2010). 3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development. *Journal of Sustainable Development*, 3(4), 17–29. doi:10.5539/jsd.v3n4p17

Przygodzki, W., Włochowicz, A., & Janowska, G. (2007). *Palność polimerów i materiałów polimerowych*. Warszawa: WNT.

Rabek, J. F. (2013). *Polimery. Otrzymywanie, metody badawcze, zastosowanie*. Warszawa: Wydawnictwo Naukowe PWN.

Rosato, D. V., Rosato, M. G., & Schott, N. R. (2010). *Plastics Technology Handbook. Volume 2 – Manufacturing, Composites, Tooling, Auxiliaries.* Highland Park: Momentum Press.

Targowski, P., Sylwestrzak, M., & Bajraszewski, T. (2009). Środowisko LabVIEW – własności i przykłady zastosowań. *Postępy Fizyki*, *60*(6), 255–256.

Wittbrodt, B. T., Glover, A. G., Laureto, J., Anzalone, G. C., Oppliger, D., Irwin, J. L., & Pearce, J. M. (2013). Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. *Mechatronics*, *23*(6), 713–726. doi:10.1016/j.mechatronics.2013.06.002

Wróblewska-Krepsztul, J., Michalska – Pożoga, I., Szczepiński, M., & Szczepiński, M. (2017). Biodegradacja – atrakcyjna alternatywa dla obecnych technik utylizacji odpadów tworzyw polimerowych. *Przetwórstwo tworzyw*, *23*(6), 579–584.

Applied Computer Science, vol. 15, no. 1, pp. 84–94
doi:10.23743/acs-2019-07

Submitted: 2019-01-11
Revised: 2019-01-28
Accepted: 2019-02-12

FGM, UMAT-USDFLD, Static, Free vibration

Sana KOUBAA [0000-0001-6369-0254]*, *Jamel MARS**, *Fakhreddine DAMMAK**

EFFICIENT NUMERICAL MODELLING OF FUNCTIONALLY GRADED SHELL MECHANICAL BEHAVIOR

Abstract

Numerical analysis of the static bending and free vibration mechanical behavior of FGM are performed using the UMAT-USDFLD subroutines in ABAQUS software. Different combinations of geometries, mechanical loading and boundary conditions are adopted. The material properties according to the coordinates of the integration points are defined in the developed numerical model. The First Order Deformation Theory is used for thin and moderately thick FG shells analysis. The accuracy and the robustness of the numerical model are illustrated through the solution of several non trivial structure problems. The proposed numerical procedure is significantly efficient from the computational point of view.

1. INTRODUCTION

Functionally graded material, known as FGMs, are non-homogeneous composite materials with mechanical properties that vary from one to three directions. They are generally composed of transition alloys from metal at the first surface to ceramic at the other opposite surface (Yanga & Shen, 2003; GhannadPour & Alinia, 2006; Draiche, Derras, Kaci & Tounsi, 2013). FGMs exhibit a smooth and continuous gradient in the composition and the material properties, which is the main difference with conventional composites which depicts a gradually properties variation with location. According to (Apetre, Sanka & Ambur, 2006), the closest similarities of FGMs are the laminated composites. However, their

* University of Sfax, National Engineering School of Sfax, Electro-Mechanical System's Laboratory, B.P 1173-3038 Street Soukra Km 3.5, Sfax, Tunisia, sana.kouba@enis.tn

properties change abruptly across the interfaces. The improved properties of composite materials have led to their use in aerospace, automotive and biomedical applications. For this, new methodologies have to be developed to characterize their mechanical response when subjected to static and dynamic solicitations. These methodologies would be incorporated into available techniques in an optimized way.

Numerous research works are available in literature to analyze the linear mechanical behavior of FG shell structures (Simo, Fox & Rifai, 1989; Chung & Chen, 2007; Ghanned & Nejad, 2013; Shariyat & Alipour, 2014). The First Order Shear Deformation theory (FSDT) is widely used (Praveen & Reddy, 1997; Lin & Xiang, 2014; Thai & Kim, 2015). The use of FSDT is justified by the fact that the classical Kirchhoff theory (CPT) neglects the effects of transverse shear and normal strains of the structure (Wali, Hajlaoui, & Dammak, 2014). The Reissner-Mindlin theory provides a correct overall assessment. Nevertheless, equations of motion are more complicated to obtain (Frikha, Wali, Hajlaoui & Dammak, 2016a). Analytical works were conducted by Abrate (Abrate, 2006) on the free vibration and static deflections of FG square, circular, and skew plates with different combinations of boundary conditions on the basis of the FSDT.

In the objective to provide the numerical solution of FGM deformation and the effect of material inhomogeneity, the theoretical formulation is typically coupled with Finite Element method. In most studies, the solution procedure can be implemented into home codes (Abrate, 2006; Frikha, Wali, Hajlaoui & Dammak, 2016b; Frikha & Dammak, 2017); other authors obtained the numerical solution using the commercial FE ABAQUS commercial software (Nie & Zhong, 2007; Alipour & Shariyat, 2012). In this regard, variations of the material properties in the transverse direction are often modeled in ABAQUS through the following technique: each layer of the composite is divided into N slices to approximate the gradual material properties variations (Mao, Fu & Fang, 2013). This method is adopted as no such type of FGM element is available in the software element library. The main drawback of this method is non-continuous segmented distribution of material properties. This conventional numerical technique is also expensive in CPU time. Results of (Mao, Fu & Fang, 2013) showed an imperfect correlation between analytical model and numerical computation.

For robustness, an alternative method consists in using the user subroutine UMAT to define the material properties according to the coordinates of the integration points when considering one layer. To the best knowledge of the authors, there are no further accessible documents in literature on ABAQUS implementation of static and dynamic response of FG shells when taking into account the continuity of material point distribution. It is within this framework that this work is performed. The material properties of FGM shell are defined according to the coordinates of the integration points using both UMAT and USDFLD subroutines, in ABAQUS software. The accuracy of the developed model is illustrated through the solution of several FG structures problems.

2. BASIC CONCEPTS AND NUMERICAL IMPLEMENTATION

A polynomial material law is adopted to control the heterogeneity of FGM properties as given by Zenkour (Zenkour, 2006), (Fig. 1):

$$P_{FGM}(z) = P_m + (P_c - P_m)\left(\frac{z}{h} + \frac{1}{2}\right)^n \tag{1}$$

where $P_{FGM}(z)$, P_m, and P_c denote, respectively, the effective material property, the metal properties and the ceramic properties. $E_{FGM}(z)$ designs the Young modulus and $\rho_{FGM}(z)$ is the density, h denotes the structure thickness and z is the coordinate measured along the thickness direction; n is the power-law index.

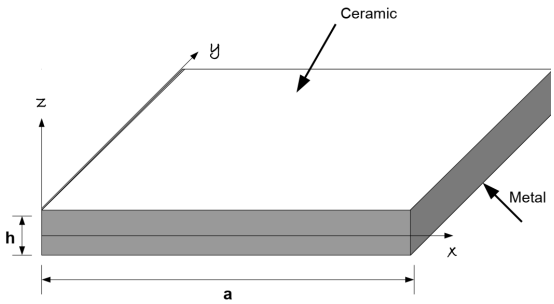


Fig. 1. Geometry of a functionally graded plate

In Finite Element model, all formulations are developed under the assumption of a linear elastic behavior and small deformations of material. According to the FSDT, the displacement components are:

$$u_x = u + z\varphi_y, u_y = v - z\varphi_x, u_z = w \tag{2}$$

φ_x and φ_y are the rotations of the transverse normal about the Cartesian axis x and y, respectively; u, v and w are the in-plane displacements and deflection of the mid-plane, respectively. The generalized displacement vector **u** is then $\mathbf{u} = [u,v,w,\varphi_x,\varphi_y]^T$. z is the thickness coordinate of the shell.

The state of deformation can be decomposed in-plane and transverse shear strains as:

$$\begin{cases} \varepsilon_{\alpha\beta}(x,y,z) = e_{\alpha\beta}(x,y) + z\chi_{\alpha\beta}(x,y) \\ \gamma_{\alpha 3}(x,y,z) = 2\varepsilon_{\alpha 3}(x,y) \end{cases}, \quad \alpha,\beta = 1,2 \tag{3}$$

where: $\varepsilon_{\alpha\beta}$, $\chi_{\alpha\beta}$, $\chi_{\alpha 3}$ are the membrane, bending and transverse shear strains, respectively. The strain vectors are presented in matrix notation:

$$\boldsymbol{\eta}_m = \begin{bmatrix} e_{11} \\ e_{22} \\ \gamma_{12} \end{bmatrix}, \quad \boldsymbol{\eta}_b = \begin{bmatrix} \chi_{11} \\ \chi_{22} \\ \chi_{12} \end{bmatrix}, \quad \boldsymbol{\eta}_s = \begin{bmatrix} \gamma_{13} \\ \gamma_{23} \end{bmatrix} \tag{4}$$

The in-plane membrane and bending and transverse shear stresses resultants:

$$N_{\alpha\beta} = \int_{-h/2}^{h/2} \sigma_{\alpha\beta}\, dz, \;\; M_{\alpha\beta} = \int_{-h/2}^{h/2} z\sigma_{\alpha\beta}\, dz, \;\; T_{\alpha 3} = \int_{-h/2}^{h/2} \tau_{\alpha 3}\, dz \tag{5}$$

The constitutive equations can then be written as a function of the in-plane and the out-of-plane linear elastic matrices depending on z:

$$\boldsymbol{\sigma} = \eta \frac{E(z)}{1-\nu^2(z)} \begin{bmatrix} 1 & \nu(z) & 0 \\ \nu(z) & 1 & 0 \\ 0 & 0 & (1-\nu(z))/2 \end{bmatrix}, \quad \boldsymbol{\tau} = \eta_s \frac{E(z)}{2(1+\nu(z))} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{6}$$

The constitutive relation between the generalized stress and strain is the following when applying the shear correction factor (Frikha, & Dammak, 2017):

$$\boldsymbol{R} = \sum \begin{bmatrix} \boldsymbol{H}_m & \boldsymbol{H}_{mb} & 0 \\ \boldsymbol{H}_{mb} & \boldsymbol{H}_b & 0 \\ 0 & 0 & \boldsymbol{H}_s \end{bmatrix} \tag{7}$$

$$(\boldsymbol{H}_m, \boldsymbol{H}_{mb}, \boldsymbol{H}_b) = \int_{-h/2}^{h/2} (1, z, z^2) \boldsymbol{H}(z)\, dz \quad , \quad \boldsymbol{H}_s = \kappa \int_{-h/2}^{h/2} \boldsymbol{G}(z)\, dz \tag{8}$$

Numerical simulation is performed using the commercial FE software ABAQUS. To avoid stress discontinuity, the material properties according to the coordinates of the integration points are implemented in two interfaces: the first interface consists on the UMAT subroutine to implement the elastic mechanical behavior along thickness using the integration point number (KSPT). The second inter face consists on the USDFLD subroutine to predefine the density field variables at a material point. In ABAQUS the integration points through the thickness of the shell are numbered successively, starting from point 1, as described in Figure 2. To obtain accurate description of FGM structure response using shell elements, the number of the through-thickness integration points (n) was carefully fixed, since a small number of integration points leads to additional error of the numerical results. Considering Simpson's approach, the point (1) is located precisely on the bottom surface of the shell. Using Gauss quadrature, point (1) is placed close to the bottom surface.

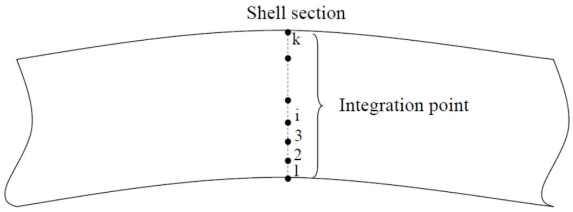


Fig. 2. Integration points defined in one layer of shell section

3. NUMERICAL RESULTS

3.1. Standard patch tests

The performance of the proposed numerical simulation is assessed with standard patch tests (Wali, Hajlaoui, & Dammak, 2014). Classically, the reference structure problems are threefold: (i) Bending of a simply supported rhombic plate, (ii) pinched hemispherical shell with 18 hole, (iii) pinched cylinder with end diaphragms. In the present study, shells are modeled with the standard quadrilateral 4-nodes element with three rotational and three translational degrees of freedom per node. Results, based on the FSDT of shell elements are obtained with the addition of an automatic computation of the shear correction factors as in (Frikha & Dammak, 2017).

FGM structure properties are: (E_m, E_c, ν_m, ν_c) = (70 GPa, 380 GPa, 0.3, 0.3) for the metal and ceramic components, respectively. All material and geometrical properties are given in a coherent system of units in the UMAT subroutine. The power-law index is $n = 6$ for all cases.

The obtained numerical results of the normalized center-point deflection are gathered in table 1. Comparison with (Wali, Hajlaoui & Dammak, 2014) show a very good accuracy. In (Wali, Hajlaoui & Dammak, 2014), a 7DOF per node, 3d-shell model was applied based on a discrete double directors shell element which is expensive from a computational time point of view. So, one can conclude that the proposed technique exhibits high performance.

Tab. 1. Results of benchmark tests

Node per side	Rhombic plate		Hemispherical shell (10^{-2})		Pinched cylinder (10^{-4})	
	Present	Wali et al.(2014)	Present	Wali et al.(2014)	Present	Wali et al.(2014)
3	1.843	7.846	4.532	5.190	0.205	0.189
5	2.761	5.186	5.153	5.398	1.822	2.157
9	2.889	3.695	5.181	5.269	3.491	3.928
17	3.073	3.348	5.204	5.220	4.302	4.525
33	3.189	3.275	5.223	5.229	4.565	4.654
100	3.278	3.268	5.237	5.232	4.672	4.746

3.2. Free vibration of FG shear-diaphragm cylindrical shell

In this section, the numerical model is applied for the case of FGM cylindrical shell subjected to free vibration with shear-diaphragm boundary conditions. The cylindrical shell has a thickness to radius ratio fixed to 0.002 and length to radius ratio fixed to 20. FGM structure properties are: (E_m, E_c,ν_m, ν_c, ρ_m, ρ_c) = = (205.098 GPa, 207.788 GPa, 0.31, 0.317756, 8900 kg.m^{-3},8166 kg.m^{-3}) for nickel and stainless steel components, respectively. For free vibration, the equations of motion take the form of a standard eigenvalue problem:

$$\left(\boldsymbol{K} - w^2 M\right)\boldsymbol{\Lambda} \tag{9}$$

where w is the eigen-frequencies of the FGM shell. The discretization of the cylinder is performed by means of S4 standard structural shell elements. The S4 shell element is widely used for industrial applications. It is suitable for thin to moderately thick shell structures. The accuracy of the proposed simulation is assessed with results in (Wali, Hentati, Jarraya & Dammak, 2015). The variation of the natural frequencies (Hz) against circumferential wave number is illustrated in Table 3. The longitudinal wave number is equal to 1. It is plausible to depict the effect of the power-law distribution choice on the frequency parameters. Some mode shapes for the shear-diaphragm FGM cylindrical shells are illustrated in Fig. 3.

Tab. 2. Frequencies (Hz), against circumferential wave number (longitudinal wave number = 1, $h = R = 0{:}002$, $L = R = 20$, $R = 1$ m).

Wave number		*Stai.st*	*n = 0.5*	*n = 1*	*n = 5*	*n = 30*	*Nickel*
2	Present Wali et al. 2015	4.5922 4.6719	4.5251 4.5955	4.5207 4.5581	4.5102 4.4838	4.5043 4.4531	4.378 4.4455
4	Present Wali et al.2015	7.2415 7.2416	7.1259 7.1136	7.1182 7.0546	7.133 6.9412	7.0891 6.8886	6.8881 6.8736
6	Present Wali et al.2015	16.989 16.909	16.713 16.605	16.694 16.467	16.660 16.203	16.629 16.083	16.159 16.048
8	Present Wali et al.2015	30.870 30.604	30.367 30.053	30.332 29.801	30.272 29.325	30.217 29.107	29.362 29.046
10	Present Wali et al.2015	48.904 48.243	48.107 47.373	48.051 46.977	47.957 46.226	47.477 45.884	46.514 45.716

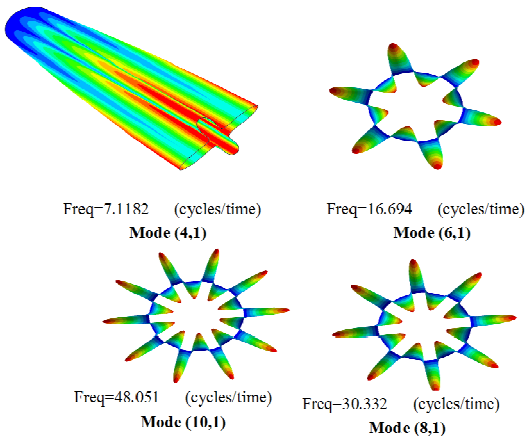


Fig. 3. Mode shapes of the FGM cylindrical shell subjected to shear-diaphragm boundary conditions

3.3. Free vibration of FG conical panel

In this section, results of free vibration of moderate thick FG conical panel clamped on the bottom surface are presented. Results are compared with numerical findings of Tornabene (Tornabene, 2009). The four-parameter power-law distribution is:

$$FGM_{a/b/c/n} : \mathrm{V}_c = \left(1 - a\left(\frac{1}{2} + \frac{z}{h}\right) + b\left(\frac{1}{2} + \frac{z}{h}\right)^c\right)^n \tag{10}$$

where, V_c denotes the ceramic volume fraction and the parameters *a, b, c* dictate the material variation profile through the FG shell thickness. Both constituents of FGM are the zirconia (ceramic) and aluminum (metal). Material properties and geometry for the zirconia and aluminum are detailed as considered in (Tornabene, 2009). The first ten frequencies for the FG conical panel as a function of the power-law exponent are gathered in Tables 3. The first six mode shapes are plotted in Figure 4. Results shows a good correlation with literature. The maximum relative error is about 1.2%. It is interesting to note that frequencies reach a minimum value for a shell made only of metal, due to the fact that aluminum has a much smaller modulus than zirconia. In fact, when increasing the power-law index, the frequencies decrease, until tending to the metal limit case. This is plausible as the ceramic content decreases by increasing the index n and the FGM shell approaches the case of the fully metal shell. This is in accordance with (Tornabene, 2009).

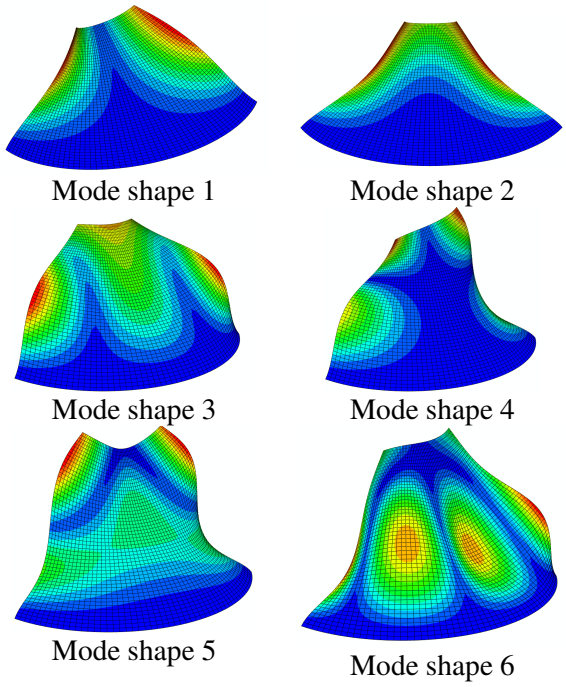


Fig. 4. Mode shapes for the FGM conical panel

Tab. 3. The first ten frequencies (Hz) for the functionally graded conical panel as a function of the power law index n ($FGM_{a=1/b=0.5/c=2}$, h/R = 0.1, L/R = 4,R = 0.5m).

Frequency (Hz)	*n = 0*	*n = 0.6*	*n = 1*	*n = 5*	*n = 20*	*n = 50*	*n = 100*	*n = inf.*
f1	80.56	80.77	80.96	83.99	79.95	77.68	77.08	75.45
f2	111.71	112.00	112.27	114.74	109.89	107.16	106.45	104.64
f3	159.61	159.90	160.21	164.14	158.08	153.73	152.57	149.50
f4	196.57	197.21	197.74	203.51	196.03	90.13	188.52	184.12
f5	260.99	261.52	262.05	268.29	258.02	251.17	249.35	244.46
f6	273.92	274.52	275.07	282.90	273.37	261.17	262.84	256.57
f7	322.90	323.50	324.14	331.57	318.93	310.48	308.26	302.45
f8	363.36	364.58	365.56	376.25	362.46	351.53	348.53	340.35
f9	398.36	399.44	400.31	412.50	399.00	386.47	382.95	373.16
f10	420.65	421.52	422.48	433.08	414.25	405.49	402.38	394.01

3. CONCLUSIONS

In this research, a numerical FE model is implemented using the UMAT-USDFLD subroutines, in ABAQUS software in order to predict the FGMs material response to static and free vibration solicitations. The material properties according to the coordinates of the integration points are defined so that stress discontinuity at the interfaces are eliminated. To the best knowledge of the authors, there are no further accessible documents in literature on ABAQUS implementation of FG shells mechanical behavior when taking into account the continuity of material point distribution. This is the main contribution of the present research. To check the performance of this technique, the present results are compared and validated with findings available in literature. It is also verified that the proposed solution procedure is significantly efficient from the computational point of view. The present study enables closed-form solutions for some fundamental solid mechanics problems, and will aid the development of finite element models for structures made of FGMs. Indeed, the present work can be applied in case of complex shells structures, contrarily to the analytical formulation which is limited to weak differentiable geometry of shell structures.

REFERENCES

Abrate, S. A. (2006). Free vibration, buckling, and static deflections of functionally graded plates. *Journal of Composites Science and Technology*, *66*, 2383–2394. doi:10.1016/j.compscitech.2006.02.032

Alipour, M. M., & Shariyat, M. (2012). An elasticity-equilibrium-based zigzag theory for axisymmetric bending and stress analysis of the functionally graded circular sandwich plates, using a maclaurin-type series solution. *Eur J Mech A/Solids*, *34*, 78–101. doi:10.1016/j.euromechsol.2011.12.004

Apetre, N. A., Sanka, B. V., & Ambur, D. R. (2006). Low-velocity impact response of sandwich beams with functionally graded core. *International Journal of Solids and Structures*, *43*, 2479–2496. doi:10.1016/j.ijsolstr.2005.06.003

Chung, Y. L. & Chen, W. T. (2007). The flexibility of functionally graded material plates subjected to uniform load. *Journal of Mechanics of Materials and Structures*, *2*, 63–86. doi:10.2140/jomms.2007.2.63

Draiche, K., Derras, M., Kaci, A. & Tounsi, A. (2013). Non-linear analysis of functionally graded plates of cylindrical bending based on a new refined shear deformation theory. *Journal of theoretical and applied mechanics*, *51*, 339– 348.

Frikha, A. & Dammak, F. (2017). Geometrically non-linear static analysis of functionally graded material shells with a discrete double directors shell element. *Computer Methods in Applied Mechanics and Engineering*, *315*, 1– 24. doi:10.1016/j.cma.2016.10.017

Frikha, A., Wali, M., Hajlaoui, A & Dammak, F. (2016a). Dynamic response of functionally graded material shells with a discrete double directors shell element. *Composite Structures*, *154*, 385–395. doi:10.1016/j.compstruct.2016.07.021

Frikha, A., Wali, M., Hajlaoui, A & Dammak, F. (2016b). A new higher order c0 mixed beam element for fgm beams analysis. *Composites part B*, *106*, 181– 189. doi:10.1016/j.compositesb.2016.09.024

GhannadPour, S. A. M. & Alinia, M. M. (2006). Large deflection behavior of functionally graded plates under pressure loads. *Journal of composite structures*, *75*, 67–71. doi:10.1016/j.compstruct.2006.04.004

Ghanned, M. & Nejad, M. Z. (2013). Elastic solution of pressurized clamped-clamped thick cylindrical shelles made of functionally graded materials. *Journal of theoretical and applied mechanics*, *51*, 1067–1079.

Lin, F. & Xiang, Y. (2014). Vibration of carbon nanotube reinforced composite beams based on the first and third order beam theories. *Applied Mathematical Modelling*, *38*, 3741–3754. doi:10.1016/j.apm.2014.02.008

Mao, Y., Fu, Y., & Fang, D. (2013). Interfacial damage analysis of shallow spherical shell with fgm coating under low velocity impact. *International Journal of Mechanical Sciences*, *71*, 30–40. doi:10.1016/j.ijmecsci.2013.03.004

Nie, G. & Zhong, Z. (2007). Axisymmetric bending of two-directional functionally graded circular and annular plates. *Acta Mechanica Solida Sinica*, *20*, 289– 295. doi:10.1007/s10338-007-0734-9

Praveen, G. N. & Reddy, J. N. (1997). Nonlinear transient thermoelastic analysis of functionally graded ceramic-metal plates. *International Journal of Solids and Structures*, *35*, 4457–4476. doi:10.1016/S0020-7683(97)00253-9

Shariyat, M. & Alipour, M. M. (2014). A novel shear correction factor for stress and modal analyses of annular fgm plates with non-uniform inclined tractions and nonuniform elastic foundations. *International Journal of Mechanical Sciences*, *87*, 60–71.

Simo, J. C., Fox, D. D. & Rifai, M. S. (1989). On a stress resultant geometrically exact shell model. part II: The linear theory; Computational aspects. *Computer Methods in Applied Mechanics and Engineering*, *73*, 53–92. doi:10.1016/0045-7825(89)90098-4

Thai, H. T., & Kim, S. E. (2015). A review of theories for the modeling and analysis of functionally graded plates and shells. *Composite Structures*, *128*, 70–86. doi:10.1016/ j.compstruct.2015.03.010

Tornabene, F. (2009). Free vibration analysis of functionally graded conical, cylindrical shell and annular plate structures with a four-parameter power-law distribution. *Comput. Methods Appl. Mech. Engrg*, *198*, 2911–2935. doi:10.1016/j.cma.2009.04.011

Wali, M., Hajlaoui, A. & Dammak, F. (2014). Discrete double directors shell element for the functionally graded material shell structures analysis. *Computer Methods in Applied Mechanics and Engineering*, *278*, 388–403. doi:10.1016/j.cma.2014.05.011

Wali, M., Hentati, T., Jarraya, A., & Dammak, F. (2015). Free vibration analysis of fgm shell structures with a discrete double directors shell element. *Composite Structures*, *125*, 295–303. doi:10.1016/j.compstruct.2015.02.032

Yanga. J., & Shen, H. S. (2003). Non-linear analysis of functionally graded plates under transverse and in-plane loads. *International Journal of Non- Linear Mechanics*, *38*(4), 467–482. doi:10.1016/S0020-7462(01)00070-1

Zenkour, A. M. (2006). Generalized shear deformation theory for bending analysis of functionally graded plates. *Applied Mathematical Modelling*, *30* (1), 67–84. doi:10.1016/j.apm.2005.03.009

Applied Computer Science, vol. 15, no. 1, pp. 95–103
doi:10.23743/acs-2019-08

Submitted: 2019-02-02
Revised: 2019-03-05
Accepted: 2019-03-20

high-tech, IT tools, employee management, development

Aneta KARASEK [0000-0002-6055-5150]*

IT TOOLS SUPPORTING EMPLOYEE MANAGEMENT IN A HIGH-TECH ENTERPRISE

Abstract

Nowadays, the rapid development of Information Technologies in several fields of socio-economic activity can be observed. High-tech companies develop or implement IT solutions in numerous areas, including employee management. In the studied high-tech enterprise, the IT solutions are used in order to facilitate employee management in recruitment and selection, development and training, evaluation, motivation, talent management and personnel-related services. The company implemented an integrated employee management system. This enabled data integration and improvement of employee management. Owing to the implementation of the tools, the company improve work efficiency in the course of procedures being standardized.

1. INTRODUCTION

At present, the dynamic development of Information Technology (IT) in several fields of socio-economic activity can be observed. The IT sector is one of the most rapidly developing branches in the global economy. In 2016, the IT software and services market was valued at approx. 1.136 billion EUR (Revenue from information technology (IT) services and software worldwide from 2005 to 2016 (in billion euros), (n.d.).). Knowledge management plays a vital role in innovation-developing enterprises. The field applies database systems presenting the decisive function on the success of high-tech manufacturers promoting knowledge management (Huang & Yao, 2018). Through knowledge transfer, organizations can

* Maria Curie-Sklodowska University, Faculty of Economics, Plac Marii Curie-Skłodowskiej 5, 20-031 Lublin, Poland, aneta.karasek@umcs.pl

provide employees with access to the resources needed to implement innovative projects (Śliwa & Kosicka, 2017). It ought to be noted that knowledge workers can enhance the innovation level, whether at the company or national level (Patalas-Maliszewska, 2014). Therefore, the management of knowledge workers as a key resource is critical in enterprises operating in the sector.

Employees in the high-tech sector develop or apply IT solutions in their daily work. As a consequence, they expect employers to introduce such tools into both HR and trainings. It can be observed that the employees seek meaningfulness in their work, enjoy intellectual and technical challenges, have a strong need for creativity and risk taking, identify more with their profession or technology than with their employing organizations, and place high value on autonomous and flexible working arrangements (Kirk & Belovics, 2007). Therefore, an adequate adaptation of IT tools employed in HRM processes is significant so that the tools support employee management and workers are satisfied with the application of the solutions.

The introduction of IT solutions depends upon several factors. The cultural context is one of these. Studies indicate that there exist discrepancies with regard to the adoption of IT solutions' functionalities. The neo-institutional theory can provide explanations for most of them (Simón & Esteves, 2016). In the United States, 67% of enterprises declared they introduced IT tools in HRM in order to improve business processes (*Sierra-Cedar 2016–2017 HR Systems Survey White Paper, 19th Annual Edition*). The largest concentration of high-tech sector enterprises can be observed in the Silicon Valley in USA. The companies are resourceful and are not only able to sense new opportunities (and threats) but make use of their abilities, introduce necessary changes or modifications when their newly founded success comes under threat. This requires the presence of employees possessing specific competences enabling them to create innovative solutions and tools which support employee management so that workers are able to meet requirements and challenges companies face.

2. ROLE OF IT TOOLS IN EMPLOYEE MANAGEMENT

IT solutions are increasingly applied in enterprises. As a consequence, they stimulate the effectiveness of business operations. In addition, they offer remote access, which is frequently exploited by employees. The solutions are used in order to facilitate employee management in recruitment and selection, development and training, evaluation, motivation, talent management and personnel service.

New technologies support recruitment and selection because they enable candidates to be matched to specific positions and duties depending upon their competences. IT solutions allow for the collection and analysis of considerable amount of data on the candidate. They also facilitate selection because they offer

the opportunity for information on the candidate, their performance, correspondence and meetings to be stored in one location. In addition, the solutions allow for novel methods aiming to evaluate candidates' competences to be implemented. The following can be enumerated among IT solutions employed in recruitment and selection (Stone, Deadrick, Lukaszewski & Johnson, 2015): e-job description, e-application of candidates and initial e-selection of the applications, e-assessment and evaluation, online interviews (e.g. videoconferences), decision-making facilitated by IT tools on the basis of the combination of predictive results and comprehensive assessment, and the evaluation of the efficiency of e-selection system and access to vital predictors. At present, these processes are supported by social media, in particular by LinkedIn, Facebook, Twitter, and discussion groups attracting specialists in specific sectors. Studies indicate that the decision regarding the application of social media in recruitment depends upon their potential job-related benefits, their ease of use, and their significance as perceived by influential individuals (El Ouirdi, El Ouirdi, Segers & Pais, 2016). Owing to the application of social media in recruitment, time to fill positions is shortened. However, the potential applicant perceptions ought to be recognized. Studies in the field indicate that perhaps some of the dynamism (i.e. more frequent updates and interactive features) associated with social media websites translates more easily into increased familiarity with a particular organization than a mere visit to a static corporate webpage does (Intindola, Lewis, Flinchbaugh & Rogers, 2017). There are differences between countries in implement functionalities and US companies make a much more extensive use of information-oriented functionalities: benefits, diversity, FAQs, employee testimonials and interview tips. (Simón & Esteves, 2016). As a consequence, becoming familiar with tools employed in recruitment in American companies seems worthwhile.

At present, enterprises implement development initiatives and are on a constant look out for novel forms of development and learning. Studies indicate that companies applied tools for learning and development in 65% of US surveyed organizations (*Sierra-Cedar 2016–2017 Survey White Paper*). Employees increasingly pursue e-learning which applies various teaching techniques: simulations, games, roleplaying, mobile and social learning, story-telling, avatars and virtual reality. As a consequence, participants become engaged in the training and have the opportunity to interact with other trainees. On the other hand, satisfaction associated with the participation in such a training is connected with the applicability of knowledge because it offers trainees a greater flexibility (Stone, Deadrick, Lukaszewski & Johnson, 2015). Training cost is also lower when compared with traditional trainings (Stone, Deadrick, Lukaszewski & Johnson, 2015). In addition, employers encourage employees to develop by means of educational platforms and Learning Management Systems (LMS). LMS offer the opportunity to improve the effectiveness of trainings and to reduce training costs. However, prior to these being implemented, one ought to consider specific

learning management solutions for organizations with dominant learning styles of employees (Ramírez-Correa, Rondan-Cataluña, Arenas-Gaitán & Alfaro-Perez, 2017). During developing a system, it is critical to take various needs of diverse recipient groups into consideration.

Gamification is introduced in order to motivate and develop employees. It enables behavior and habits of employees to be modified and employees' engagement in trainings to be boosted. Companies use mechanisms of games in order to motivate behavior significant from their point of view. Such mechanisms exert an impact upon engagement, experimenting and employee performance (Werbach & Hunter, 2012). This is especially valid for employees representing generation Y (Chamorro-Premuzic, Akhtar, Winsborough & Sherman, 2015). Owing to the use of games, employee behavior may be controlled and workforce may be stimulated to undertake actions which may seem difficult to complete.

Tools facilitating talent management gain particular significance for high-tech companies because talented employees enable new company development opportunities to be generated. Studies indicate that companies applied tools for talent acquisition in 80% of US surveyed organizations (*Sierra-Cedar 2016–2017 Survey White Paper*). At present, conditions associated with increasing requirements voiced by talents result in companies rethinking tools they apply. The integration of talent data with pan-organizational business and operational data constitutes one of the current trends. This has particular importance with regard to the organization's innovation (*Sierra-Cedar 2016–2017 Survey White Paper*). This stems from the fact that several characteristics, e.g. personality, are difficult to be measured. Therefore, companies apply big data in talent management in order to make apt decisions pertaining to talented workers, which exerts an impact upon organizational performance as well (Russell & Bennett, 2015) . In addition, companies use new tools for evaluating workplace talent and potential, e.g. machine-learning algorithms, social sensing technology and gamified assessment tools (Chamorro-Premuzic, Akhtar, Winsborough, & Sherman, 2017).

At present, employee performance is supported by IT tools facilitating the aggregation of data and information on the performance. 68% US surveyed organizations applied tools for performance management (*Sierra-Cedar 2016–2017 Survey White Paper*). The assessment based upon employee performance is significant because it consolidates their motivation and contributes to improved organizational effectiveness (Arvanitis, Seliger & Stucki, 2016). IT tools applied in the performance review offer information on employee productivity. As a consequence, actions aiming to improve the situation and career development management are possible (Bondarouk & Brewster, 2016). Studies indicate that employees whose performance was assessed by online tools manifested significantly higher performance than those evaluated on the basis of traditional instruments (Payne, Horner, Boswell, Schroeder, & Stine-Cheyne, 2009). Scholars indicate the possibility of applying a fuzzy logic concept in employee performance review.

This enables for costs associated with the review to be reduced (Samuel, Omisore, & Atajeromavwo, 2014). Access to specific information on employees opens the opportunity for suitable actions to be taken which aim to improve the effectiveness of initiatives undertaken by employees.

At present, HR management tools are the ones which are the most frequently applied. The organizations that are operating in a vibrant business market (e.g. high-tech firms) need to emphasize on evidence-based approach and implement transformative HR practices (Bodla & Ningyu, 2017). These improve employee management processes, offer access to specific data and the possibility of employee self-service. Owing to a growing automation of administrative work and ready access to data, decision-making is decentralized. This enables those responsible for HRM to focus more effectively upon complex, judgement-oriented and demanding duties (Marler & Parry, 2016). Employees are perceived as active consumers of HRM services in the employee-centered approach. Therefore, companies implement solutions facilitating HR flow and making the process as effective as possible.

Studies indicate that employees create value from the provided HRM services by utilizing their knowledge and skills. Authors highlight that HRM service providers are able to improve HR service utility and HR value perception by offering improved value propositions (e.g. HR portals with higher user-friendliness, new services adjusted to users' needs) (Meijerink, Bondarouk & Lepak, 2016). This may motivate employees to use HRM services more effectively (Meijerink, Bondarouk & Lepak, 2016). It is of particular significance in relation to employees of the high-tech sector, who create and apply IT solutions in their daily work. In addition, these employees demand independence and high standards of services from their employers. As a consequence, studies aiming to identify and assess the application of IT tools in managing employees of the sector seem valid.

3. DATA AND METHODOLOGY

The objective of the study was to identify and assess the application of IT solutions in the following fields: recruitment and selection, development and training, evaluation, motivation, talent management, and HR in a high-tech company located in the Silicon Valley in USA. The study was conducted by means of a case study approach in 2015. Results were analyzed on the basis of the analysis of organizational documents, interviews and observations.

4. RESEARCH RESULTS

Enterprise „Z" was established in 2012. In 2014 it received a distinction from Forbes magazine. The company develops software facilitating personnel management. In 2015, the company employed 1500, who worked primarily in San Francisco, California and Scottsdale, Arizona. The dynamic development of the enterprise resulted in the number of employees reaching 2000 in 2016.

The employment of workers contributing to the realization of operations is of critical importance for the functioning and development of a high-tech company. In order to manage the recruitment process and applicant pool, the company employs the ATS system in recruitment and selection. In addition, recruiters may filter work applicants with regard to the score and answer they offered to a particular question. As a consequence, the cooperation of recruitment teams and joint review of applications and the approval of employment opportunities are possible. In addition, owing to alerts and notifications, applicants are up-to-date on the process. The system has been employed in the company since 2014. This was observed to facilitate communication and the realization of the process. According to employees' opinions, the application of the solution prevents bias. This is because decisions are based upon the review of specific skills, characteristics and qualifications. It also enables talented workers to be identified. It can be argued that selection was effective, which seems to be acknowledged by a low employee turnover. In addition, big data was analyzed on the basis of a specific algorithm identifying required employee competences. Respondents also recognized threats associated with the solution. The analysis may help to indicate a candidate who possesses suitable knowledge, references and experience in the execution of projects. However, personality features remain largely unknown. In addition, the selection of appropriate keywords which would allow for these to be checked in the available information posed problems as well.

Employee development is supported by e-learning and education platforms. In order to develop the competences, a learning management system was introduced. The system supports the development of employee competences. Users highlighted benefits emerging from the application of the system. It enabled the development of skills to be monitored and supplied and tracked tailor-made education plans and materials. In addition, the interface and navigation were user-friendly. The solution allowed for several development-related initiatives, which addressed a broad spectrum of employees, to be conducted. Social media were rarely employed in company "Z". Respondents indicated that, due to the fact that they spent most of their working time in front of a computer screen, they found the development of relations via direct contact significant.

The company employed an integrated employee management system. It enabled employee performance to be reviewed, HR affairs to be managed, employees to be motivated and remunerated. The system also allowed for employee self-service. The company believes that owing to data integration, effective employee

management is possible. The tool applied in the company features a panel for managers enabling crucial operations to be done, including the employment of a new worker, change of positions or salary, etc. Reports generated from business intelligence systems supported daily work of managers because they allowed for HR and financial data to be accessed, edited and analyzed in real-time.

5. CONCLUSIONS

Human resources management in high-tech companies is facilitated by IT tools enhancing HRM processes. The IT solutions prevent bias because decisions are made on the basis of suitable skills, features and qualifications of employees. Studies in the field indicate that the solutions enhance communication and delivery of HR processes. As a consequence, the management are able to focus upon strategic operations. In addition, owing to the application of IT tools, data and information are compiled in a single location. This facilitates access and enables improved personal decisions to be made.

Users play a considerable role in the application of IT tools in recruitment and selection, development and training, evaluation, motivation, talent management and HR. They are the ones who create content, use the tools and make decisions based upon the data provided in these. Therefore, it is vital to examine user needs, user experience, and benefits they obtain in connection with the tools, and opportunities for improving the solutions.

Owing to the application of IT tools in employee management, data is collected and used in the decision-making process. This results in administrative costs being reduced. It ought to be noted that the implementation of IT solutions enhances services addressing stakeholders (i.e. work applicants, employees and owners). This is of vital importance for high-tech companies, whose employees seek innovative solutions and require support in developing competences, motivation or stimulation of talented employees.

The practical implications include the fact that the enterprises of the high-tech sector may utilize the aforementioned good practices in supporting their employees. The surveyed company gained experience in the field and devoted time to reflect upon the needs of users and benefits offered by the solutions. Owing to the implementation of the tools, the HR department may improve work efficiency in the course of procedures being standardized. However, the solutions ought to be adjusted to specific companies. The author is aware of the limitations of the present study. One of these is the lack of quantitative data. However, the consent to make the data available, along with information on the applied solutions, was problematic due to the fact that companies seek to protect their knowledge and know-how. Prospective studies and the expansion of the research model to encompass recent developments in artificial intelligence and mobile apps are foreseen.

REFERENCES

Arvanitis, S., Seliger, F., & Stucki, T. (2016). The relative importance of human resource management practices for innovation. *Economics of Innovation and New Technology*, *25*(8), 769–800.

Bodla, A. A., & Ningyu, T. (2017). Transformative HR practices and employee task performance in high-tech firms: The role of employee adaptivity. *Journal of Organizational Change Management*, *30*(5), 710–724. doi:10.1108/JOCM-02-2016-0030

Bondarouk, T., & Brewster, C. (2016). Conceptualising the future of HRM and technology research. *International Journal of Human Resource Management*, *27*(21), 2652–2671. doi:10.1080/09585192.2016.1232296N

Chamorro-Premuzic, T., Akhtar, R., Winsborough, D., & Sherman R. A. (2017). The datafication of talent: how technology is advancing the science of human potential at work. *Current Opinion in Behavioral Sciences*, *8*, 13–16. doi:10.1016/j.cobeha.2017.04.007

Revenue from information technology (IT) services and software worldwide from 2005 to 2016 (in billion euros). (n.d.). In *The Statistics Portal.* Retrieved March 1, 2019 from https://www.statista.com/statistics/268632/worldwide-revenue-from-software-and-it-services-since-2005

Huang, P., & Yao, Ch. (2018). Key success factors in high-tech industry promoting knowledge management. *Journal of Interdisciplinary Mathematics*, *21*(2), 509-517. doi:10.1080/09720502.2018.1451607

Intindola, M. L., Lewis, G., Flinchbaugh, C., & Rogers, S. E. (2017): Web-based recruiting's impact on organizational image and familiarity: too much of a good thing? *The International Journal of Human Resource Management*. doi:10.1080/09585192.2017.1332672

Kirk, J., & Belovics, R. (2007). The high- tech industry and its workers. *Journal of Employment Counseling*, *44*(2), 50–59. doi:10.1002/j.2161-1920.2007.tb00024.x

El Ouridi, M., El Ouirdi, A., Segers, J., & Pais, I. (2016). Technology Adoption in Employee Recruitment: The Case of Social Media in Central and Eastern Europe. *Computers in Human Behaviour*, *57*, 240–249. doi:10.1016/j.chb.2015.12.043

Marler, J. H., & Parry, E. (2016). Human resource management, strategic involvement and e-HRM technology. *The International Journal of Human Resource Management*, *27*(19), 2233–2253. doi:10.1080/09585192.2015.1091980

Meijerink, J. G., Bondarouk, T., & Lepak, D. P. (2016). Employees as Active Consumers of HRM: Linking Employees' HRM Competences with Their Perceptions of HRM Service Value. *Human Resource Management*, *55*(2), 219– 240. doi:10.1002/hrm.21719

Patalas-Maliszewska, J. (2014). Can local knowledge workers significantly contribute to the growth of the national level of innovation? *Applied Computer Science*, *10*(1), 44–54.

Ramírez-Correa, P. E, Rondan-Cataluña, F. J., Arenas-Gaitán, J., & Alfaro-Perez, J. L. (2017). Moderating effect of learning styles on a learning management system's success. *Telematics and Informatics*, *34*(1), 272–286. doi:10.1016/j.tele.2016.04.006

Payne, S. C., Horner, M. T., Boswell, W. R., Schroeder, A. N., & Stine-Cheyne, K. J. (2009). Comparison of online and traditional performance appraisal systems. *Journal of Managerial Psychology*, *24*(6), 526–544. doi:10.1108/02683940910974116

Rusell, Ch., & Bennett, N. (2015). Big Data and talent management: Using hard data to make the soft stuff easy. *Business Horizons*, *58*(3), 237–242. doi:10.1016/j.bushor.2014.08.001

Samuel, O. W., Omisore, M. O., & Atajeromavwo, E. J. (2014). Online fuzzy based decision support system for human resource performance appraisal. *Measurement*, *55*, 452–461. doi:10.1016/j.measurement.2014.05.024

Sierra-Cedar 2016–2017 HR Systems Survey White Paper, 19th Annual Edition

Simón, C., & Esteves, J. (2016). The limits of institutional isomorphism in the design of e-recruitment websites: a comparative analysis of the USA and Spain. *The International Journal of Human Resource Management*, *27*(1), 23–44. doi:10.1080/09585192.2015.1004186

Stone, D. L., Deadrick, D. L., Lukaszewski, K. M., & Johnson, R. (2015). The influence of technology on the future of human resources management. *Human Resource Management Review*, *25*, 216–231. doi:10.1016/j.hrmr.2015.01.002

Śliwa, M., & Kosicka, E. (2017). A model of knowledge acquisition in the maintenance department of a production company. *Applied Computer Science*, *13*(3), 41–54. doi:10.23743/acs-2017-20

Werbach, K., & Hunter, D. (2012). *For the Win: How Game Thinking Can Revolutionize Your Business*. Wharton Digital Press.