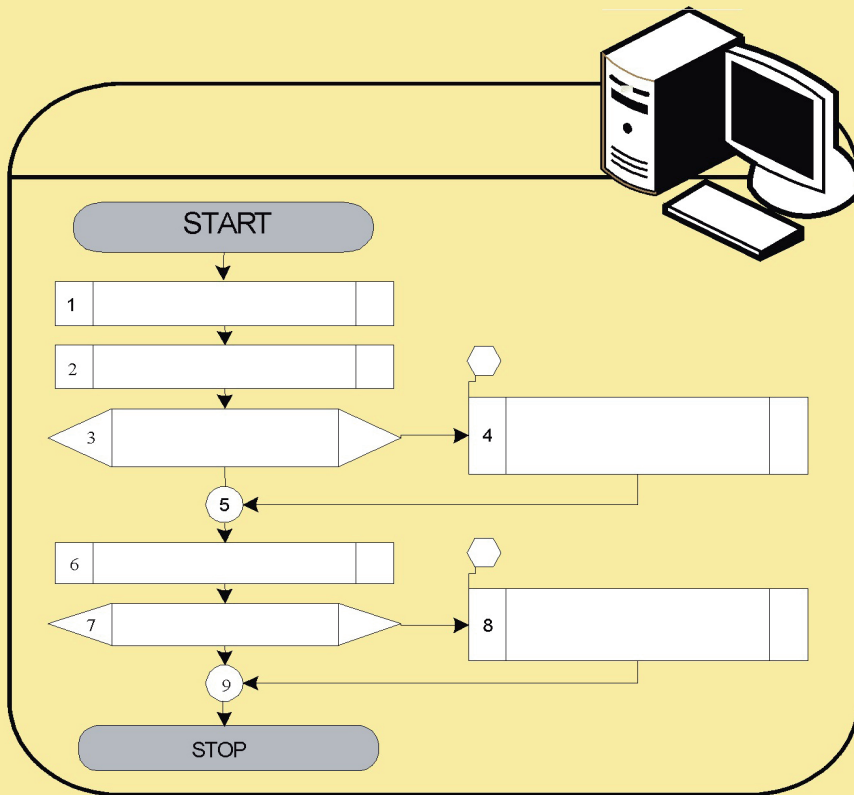


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APPLIED COMPUTER SCIENCE

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mobile robots, python computer language, programming

*Andrzej PIOTROWSKI**

AN ANALYSIS OF THE USE OF THE PYTHON LANGUAGE IN ROBOT APPLICATIONS

Abstract

The paper has analyzed the possibility of using the Python computer language in programming mobile robots. The designed and constructed test stand – a caterpillar mobile robot, enables the testing of wireless control algorithms, responses to events, I/O device programming methods and path selection algorithms. The software applications(client and server) written in the Python computer language have been developed and analyzed. A partial listing of the program source is included. The usefulness of Python in robot applications was confirmed.

1. INTRODUCTION

The end of the 20th century and the beginning of the 21st century mark a period of the expansion of autonomous robots. The development of computer technologies has contributed to an increase in productivity with the simultaneous miniaturization of computerised systems. Control systems have become smaller and capable of being installed in small-sized devices. An example are drones (Fig. 1) – robotized flying machines of a size from several dozen centimetres to several meters [11, 17]. Particularly small versions are popular on the consumer market and are used for filming object or invigilating people. In the case of operational drones, in addition to vision systems, the drones are equipped with advanced combat systems that enable the carrying out of "surgical" attacks on chosen targets. As a rule, drones are remotely controlled by the operator, who is dozens of kilometres away from the battlefield, using radio waves (most often via a satellite connection). This means that most important decisions are theoretically made by a human.

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However, in the event of a disturbance or break in connection, the robot's control system and its operating software are able to independently make a decision on the continued operation of the drone (to retry to make connection with the operator, automatically return to the base, or to launch an attack on the selected target). Autonomous robots offer also a method for exploring the space. Small-sized and a few hundred grams in weight, mobile robots provide an excellent alternative to dangerous manned missions. Power supplied from photovoltaic batteries and furnished with advanced control systems and exploration tools, they are able to practically independently conduct geological surveys or to analyze the composition of the atmosphere on a remote planet. An example are the successful Mars exploration attempts with the use of the US Sojourner or Curiosity rovers (Fig. 1a) [11, 17].

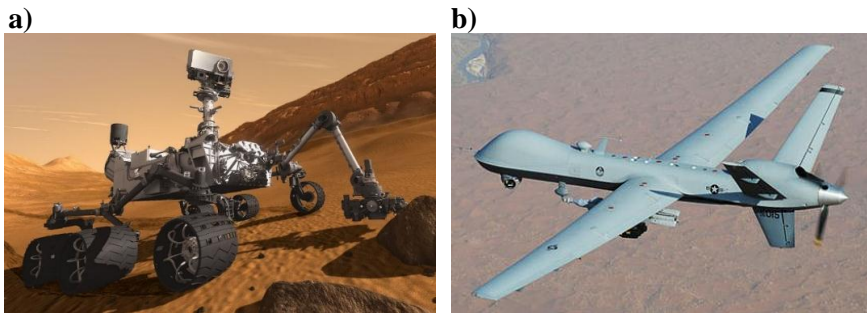


Fig. 1. a) Curiosity – The Mars Rover – A visual concept [17], b) MQ-9 Reaper [11]

Autonomous robots are constructed, as a rule, based on advanced electronic subassemblies. The first models used PLC controllers adapted to the purposes of robotics and were programmed based on languages typical for industrial applications, e.g. graphical languages, such as the Sequential Function Chart (SFC) language, the Function Block Diagram (FBD) language and the Ladder Diagram (LD) language; and text languages, such as the Structured Text (ST) language and the Instruction List (IL) language. The use of text languages allowed possible reprogramming of the robot that was situated at an immense distance from Earth, as it required short and easy-to-compress text messages. The next stage in the development of robotic systems were control systems relying on micro-controllers. For their programming, programming languages from the C and C++ families and, for simple applications, the adapted BASIC language were used. Created applications were then compiled and stored in the memory of the controller or microcontroller. Their characteristic feature was a small capacity of the operating memory, which required short applications to be created. The most recent solutions and the immense miniaturization of computer systems allow computers to be used in robot systems, which are furnished with advanced, highly efficient processors, a large operating memory and numerous I/O ports enabling the control

of a huge number of external devices. Unlike microcontrollers, a classic operating system known from home use is possible to be run on a such a computer. This is a great asset. The use of a traditional operating system from the Microsoft Windows or Unix/Linux family allows alternative programming languages to be used. For example, the very popular Raspberry Pi microcomputer uses the Linux operating system, while the pre-ferred language for the operation and programming of the GPIO connector is the Python language [5, 16]. This constitutes a total departure from the traditional perception of programming robots as a very complex task to be carried out by advanced programmers using the C language or its derivatives.

By observing the changes occurring in the construction and programming of robots, the possibilities of using the Python language in mobile robot applications [11, 14, 19] were examined. The investigation was divided into several stages. The first stage included the selection, construction and building of a test stand; the second stage covered the design and making of a control systems based on the state-of-the-art microcomputer systems; the third stage encompassed the writing of a client-server standard control application using the Python language; and the four stage summed up the experiment results. All the above-mentioned work was completed at the Institute for Mechanic Technologies of the Czestochowa University of Technology with a contribution by the members of scientific associations active at the Institute.

2. THE TEST STAND – A CATERPILLAR MOBILE ROBOT

2.1. Mechanical construction

In terms of their design solutions, autonomous mobile robots can be divided into two groups. The first group includes vehicles using a classic or modified wheel system with swivel wheels allowing the choice of the direction. The second group consists of caterpillar vehicles that use an independent drive of two mutually parallel caterpillars. The control of each caterpillar allows changing the vehicle's movement direction without having to construct a complex steering system, which is characteristic of wheeled vehicles. This simplifies the construction of the robot and facilitates its control. When building the test stand, a decision was made to construct a caterpillar vehicle driven by two independent stepper motors. The construction of a small robot of dimensions of 200 x 180 x 120 mm and a weight of about 4 kg was assumed. These dimensions were determined by the size of the control system which was built based on a Raspberry Pi microcomputer in version 2 [8, 13, 15, 20].

The robot was designed within the SolidWorks 2015 software program by 3DS. Several conceptual versions of the robot were developed in the form of three-dimensional CAD models. Using SolidWorks' advanced programming

functions, the analysis of the design and kinematics of the caterpillar vehicle was made, which enabled the selection of the simplest and cheapest solution. The design was simplified to a maximum. The originally assumed system of spring shock absorbers and tensioners was abandoned for simple rockers that performed two functions: shock absorbing and caterpillar tensioning. The drive system was simplified to use only five wheels: two large road wheels (front and rear), two small rocker-mounted wheels and a single driving wheel positioned above the rear wheel, connected with the propulsion motor with a rack system (Fig. 2a). It should be noted, at the same time, that for the construction of a heavier larger-size model, the original concept relying on damped road wheels (with torsion springs) and a classic front wheel and a rear driving wheel will be used.

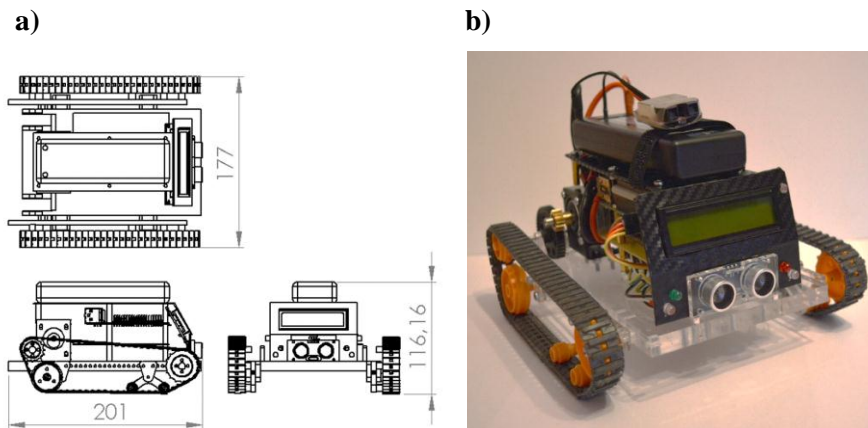


Fig. 2. The test stand – a caterpillar mobile robot [source: own study]

The basic constructional element is a floor panel with brackets supporting the drive system and control system elements. It was made from plastic (acrylic glass) using a laser cutting technology, which ensured a high accuracy and aesthetics of robot execution (Fig. 2b). Distance sensors, a camera and illumination elements to light up the space around the vehicle were mounted on the floor panel brackets [2,12]. The robot is additionally furnished with an LCD screen for testing purposes. It is used for displaying commands received by the rover's control system (the response to the received command). This enables a very fast analysis of any errors without having to logging on and verifying the file containing information on the operation of the software and the control system (error log).

2.2. The control system and electric & electronic elements

The heart of the control system employed in the test stand is a Raspberry PI 2 computer. This is the second version of the Raspberry Pi mini-computer developed in 2012 in the UK by the Raspberry Foundation [7]. The size of a credit card, built based on an ARM-architecture processor being typical rather of mobile phones, the microcomputer turned out to be a great success. In spite of its, at first, low computing performance, it became a standard in building of, not only amateur, control systems. Its greatest asset distinguishing it from other constructions of this type is a 40-pin GPIO connector (I2C, SPI, UART interfaces) terminated outside, which enables a huge number of peripheral devices (such as stepper motors, controllers, robot control systems, etc.) to be connected. The PI 2 Raspberry system used on the test stand is distinguished, compared to the first version, by a more efficient processor and the RAM memory expanded to 1 GB (table 1).

Tab. 1. The characteristics of the Raspberry PI 2 microcomputer [14]

Processor	Broadcom BCM2836 quad core Cortex A7 @ 900MHz
GPU	VideoCore IV
Memory	1GB SDRAM
Card reader	Memory card reader micro SD
Outputs	HDMI 1.4, AV (3.5mm jack)
LAN	Ethernet 10/100Mb
Ports	4x USB 2.0 ports, 1x micro USB port
Extensions	40 pins GPIO, camera and monitor connector
Power	5V from micro USB port

A feature that qualifies the Raspberry PI 2 microcomputer to be used in mobile systems is its low energy demand. The system is supplied with a voltage of 5V and a (maximum) current intensity of 2A from a LiPol Redox Racing 4000 mAh battery pack (Fig. 3), which is sufficient for 2 hours of operation at the maximum energy consumption (operating motors, the additional lighting switched on, continuous communication between the Client and the Server, 100% loading of the Cortex A7 processor). Batteries of this type are characterized by a large discharge current, regardless of the battery pack charging level. Therefore, the current efficiency does not decrease with the decrease in voltage, which results in stable power supplying [12].

All the system elements are connected to the Raspberry PI 2 GPIO socket (Fig. 3). These are two SY35ST28-0504A stepper motors controlled by A4988 systems. The motors drive the robot's caterpillars via a reduction gear (two gear wheels). For the assessment of the distance from an obstacle, an HC-SR04 ultrasonic sensor is used, which measures the distance in the range of 20 to 2000 mm

with an accuracy of 3 mm. It was assumed in the design that the robot would be controlled by the operator. However, for safety reasons (communication breaking, no visibility) and for testing purposes (testing the automatic path selection algorithms), the robot was equipped with a system for determining the distance from any objects being in its way. It has been provided for in the developed algorithm that in case of no reaction on the operator's part, the robot will automatically stop at a distance of 30 mm before the obstacle and a message of about a possible collision will be displayed on the screen.

Other elements connected to the GPIO socket include signalling and illuminating diodes and an LCD display controlled by the LCM 1602 system performing the function of a converter between the 12C bus and the LCD screen. For communication between the user's computer or smartphone and the test stand, a wireless connection system operating in the WiFi technology is used. For one of the Raspberry PI 2 USB ports, a TL-WN725N network card is connected. The transmission protocol is the classic TCP/IP v. 4 protocol. The use of WiFi transmission in the 801.11n technology simplifies the programming of the robot. The range is several hundred metres in an open area, and the transmission is encoded, which ensures high security. The designed and constructed test stand is universal and enables many hardware and programming solutions to be tested. The test stand is scaled, thus allowing additional devices to be installed on the robot, such as a camera, a sampling system, etc. It enables the analysis of using the Python language for the control of a mobile system to be made.

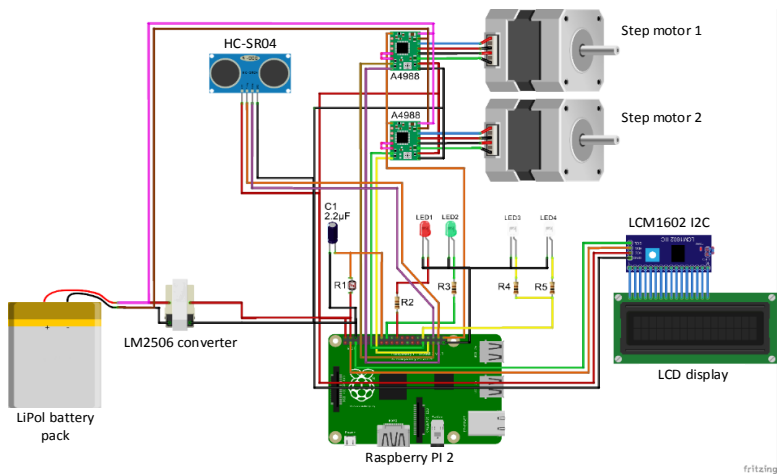


Fig. 3. A schematic diagram of the test stand control system [source: own study]

3. BUILDING THE CONTROL APPLICATION IN THE PYTHON

The Python language was created in 1991 by the Dutch programmer Guido van Rossum. It is a general-purpose high-level programming language with an extended package of standard libraries. The syntax is distinguished by transparency and conciseness. Python supports various programming paradigms, such as object-oriented, imperative and, to a lesser extent, functional. It has a fully dynamic file system and automatic memory management. It is an interpreted language, therefore it is often used as a script language. To operate correctly, it requires the presence of a special, operating system-dependent interpreter, which analyzes the source code, compiles and then executes it. The Python language interpreters are available practically for all operating systems. Its chief asset is openness – it is being developed by Python Software Foundation as an OpenSource project [14, 17].

On the test stand (mobile robot), the Raspbian Jessie operating system was used, which is based on the Linux system architecture. It is a free distribution optimized for correct running on the Raspberry Pi 2 microcomputer platform. As it is an Open Source distribution, it is possible to interfere in the system's code to adapt it to a specific task. Due to the small size of the robot and its nature (a mobile device), the connection of peripheral devices in a classic manner was impossible. A terminal connection using an SSH protocol stack was used. As a result, a remote, textual and, most importantly, encrypted connection in a client–server mode was obtained. Due to the limitations of the Raspberry PI 2, the control application in the Python language was created within the dedicated IDLE Python version 3.5 programming environment on a traditional PC in the MS Windows 7 environment. The written program was then copied onto the micro-SDHC memory card of the Raspberry Pi 2 microcomputer located in the robot using the WinSCP application.

The construction of the test stand and the project assumptions explicitly determined the software structure. The application was divided into two independent, but closely working parts. The first part is software operating on the robot, performing the role of the server, and the second part – client software running on the operator's computer or smartphone (table 2).

Tab. 2. Client and server tasks [source: own study]

Client tasks	Server tasks
<ul style="list-style-type: none"> • making connection with the server, • running the pygame library, • reading out the information on the pressed key, • matching the command to the operator's reaction • sending the command to the Server, • sending the relevant command in the case of an error or no response. 	<ul style="list-style-type: none"> • the GPIO pins definition, • defining the GPIO pins as an Input/Output, • setting the initial states of the GPIO pins, • reading in the definitions of steps, moving directions, measurement and additional illumination, • receiving the command from the Client, • taking the relevant action according to the received command.

3.1. Server software

The server's software is run on the Raspberry Pi 2 microcomputer. Its basic job is to receive the command transferred from the Client and to take relevant actions (Fig. 4). The program 'Server' is run automatically upon the operating system start. The Server connects with the Client and remains in constant contact with it. The communication takes place via the UDP protocol. This is a connectionless protocol of the fourth layer of the OSI/ISO model. This protocol has no mechanisms for the control of the flow and retransmission of packages (other OSI/ISO model layers are involved in the correction of errors). An advantage is a higher speed of data transmission between the Server and the Client. The UDP protocol does not burden the host with additional activities, whereby any delays are very small compared to other protocols [18].

The Server's program has been written in the Python language version 3.5 (2016) using libraries containing the procedures of I/O device handling and standard computer functions operation. The Python language version dedicated to the Raspberry PI 2 includes also libraries specific to microcomputer assemblies (operation of the GPIO connector) [16, 18].

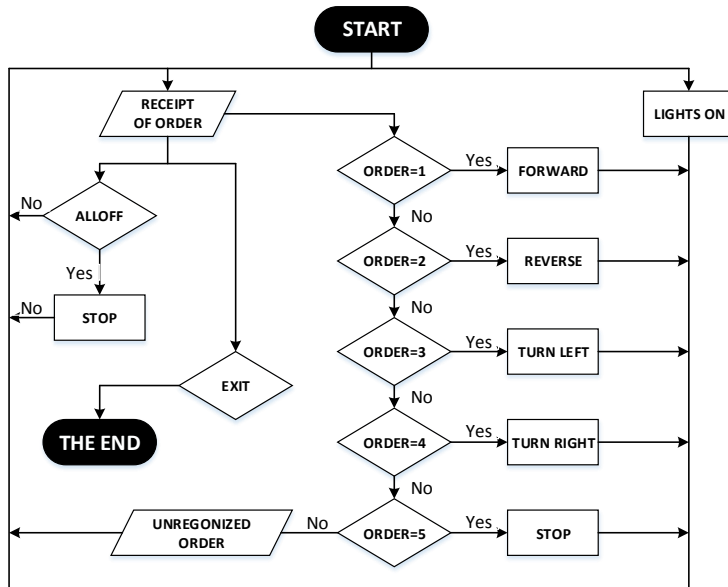


Fig. 4. The block diagram of the application 'Server' [source: own study]

When creating the Server application, the following were used:

- SocketServer – a library responsible for making a connection and creating the so-called connection socket, in accordance with the IP V.4 protocol,
- RPi.GPIO as GPIO – a library for handling Raspberry Pi 2 GPIO terminals, which enables the control of GPIO terminals without giving directly their logic addresses, and the indication of a logic stage (0 or 1) on a specific pin; to define specific pins, respective numbers are used,
- time – a library that enables the use of a clock in the program code, thanks to which it is possible to count the time, e.g., when measuring the distance,
- lcd driver – a library that handles the LCD display and the I2C converter dedicated to its operation; the library enables the addressing of the I2C converter, textual entering the text to be displayed on the display and controlling the backlight of the LCD display,
- socket – another library designed for the operation of the connection socket; it performs the function supplementary to that of the SocketServer library.

The Server takes actions as per the command received from the Client (Fig. 4). These actions include: controlling the stepper motors, measuring the distance from an obstacle, controlling the lighting, etc. The detailed analysis and listing of the Client and Server programs would go far beyond the scope of this paper. Therefore, only the most important fragments of the program will be covered. According to the block diagram (Fig. 4), the programs consist of many procedures

and functions and are divided into blocks, each of them performing a specific task. For example, one of the functions performed by the Server is, in the case of insufficient external lighting, the additional illumination of the space in which it moves. The definition of the instruction `light()` in the Python language is as follows:

```
def light ():      # definition responsible for measurement
# illumination
    light = 0
    GPIO.setup(photo, GPIO.OUT)
    GPIO.output(photo, False)
    time.sleep(0.0002)
    GPIO.setup(photo, GPIO.IN)
    while (GPIO.input(photo) == GPIO.LOW): light += 1
    if light >= 1000:      GPIO.output(ledb, True)
    elif light < 1000:    GPIO.output(ledb, False)
    print 'Light intensity level: %i' %light
```

The purpose of this instruction is to measure the light intensity using a photoresistor installed on the robot. The Raspberry Pi 2 examines the step response on the pin, to which the photoresistor is connected. The step response is the testing of the system's response to the change in the signal, which is generated on the input connector, from the low to high state. The testing involves the measurement of the time of capacitor charging up to a level of 1.65V (this is the level of the receipt the high state on the input pin). This time is dependent on the resistance that the photoresistor has at the moment when the light falls upon it. The lower the photoresistor resistance, the faster the capacitor charging voltage increases [6]. The Raspberry Pi examines the time between the high and low states. Thereby, the lighting level is defined. If the lighting turns out to be too low, the 'Server' application lights up the working space by passing a signal to the GPIO pins [16,18], to which white LEDs are connected. If the value is greater than or equal to 1000, the pin state will be set as high and the LEDs will light up. If the value is less or equal to 1000, the diodes will go off.

Another task of the Server is to perform the measurement of the distance as it moves forward. The definition of `measurement()` is as follows:

```
def measurement():      # measurement of distance from obstacle
                        # via HC-SR04 sensor
GPIO.output(trig, True) # sending impulse 10µs in length
time.sleep(0.00001)
GPIO.output(trig, False)
start = time.time()    #start time measurement
while GPIO.input(echo)==0:
```



```

start = time.time() #waiting for echo
while GPIO.input(echo)==1: #stopping time
stop = time.time()

# computing impulse length
impulse = stop-start
#computing distance (34300 sonic speed in air cm/s)
global distance
distance = impulse * 34300
distance = distance / 2
print "Distance from obstacle: %0.1f" %distance

```

The definition of measurement() sends out a 10 μ s-long impulse to the TRIG pin of the HC-SR04 ultrasonic sensor. The signal generates an ultrasonic wave to be emitted by the sensor. This is followed by a period of waiting for the signal on the ECHO pin, to which the high state is fed as soon as the ultrasonic wave has returned to the sensor. The time measured between the end of feeding the signal onto the TRIG pin and the appearance of the high state on the ECHO pin defines the distance of the obstacle from the sensor. For this purpose, the velocity of sound wave propagation in air should be taken into account, which is approximately 34300 cm/s. To calculate the distance, the time value is multiplied by the velocity of sound propagation in air, that is 34300 cm/s. Thus obtained distance is the path covered by the sound from the sensor to the obstacle and back; therefore, in order to obtain the distance from the obstacle, the result is divided by 2. The of the presented procedures will be the definition of stepper motor operation. There are several such procedures in the program, which are responsible for motor rotation direction (forw(), back(), right(), left() and stop()). The procedures are very similar. The only difference arises from the selection of the required motor rotation direction. For example, the definitionforw():

```

def forw():      # instruction for robot moving forward
    GPIO.output(direction1, True)
    GPIO.output(direction2, False)
    GPIO.output(ledz, True)
    GPIO.output(ledc, False)
    print "\nJade forward ... \n"
    lcd lcd_clear()
    lcd lcd_display_string("Go", 1)
    lcd lcd_display_string("  forward!", 2)
    step()

```

The first item is the definition of the logic state on the direction pins direction1 i direction2. The high logic state at the terminal direction1 means motor rotations in the anti-clockwise direction, while the low logic state on the direction2 pin is responsible for the motor movement in the clockwise direction.

Another item is operation signalling with LEDs; the high state on the ledz pin lights up the green LED, while the low ledc state puts off the red LED. This is followed by clearing the LCD display (lcd.lcd_clear()) and displaying text information on the selected instruction (lcd.lcd_display_string()) on the LDC display. After ending of the signalization, the start of the stepper motors follows – the instruction step():

```
def step():                                # motor step definition
    GPIO.output(en, False)
    motor1.start(1)
    motor2.start(1)
```

The definition step() feeds the low state onto the pin en, whereby the stepper motors are able to rotate. Then, feeding of the stepper motor control signal is started. For controlling the stepper motors, the PWM signal was used, as its generation does not cause any delays associated with maintaining the state of the pins, by specifying appropriate time values in the program. Owing to this solution, no additional delays occur.

For the receipt of the command and its proper definition, the command_receipt class is responsible. This class is also responsible for launching the definition responsible for lighting the working space – the definition light(). The next step is the receipt of the command from the Client. After receiving the command, the Server starts its analysis. In the case of the 'ALLOFF' and 'EXIT' commands, which are responsible for stopping the motors should the Client program abort, the Raspberry Pi sets the high state on the pin en and lights up the red LED.

Similarly, procedures and functions responsible for the operation of all test stand elements have been created. Written in the Python language, the 'Server' application is versatile and scalable. The program skeleton has been created as split into functional parts, whereby adding further elements to the robot will only require writing in additional procedures to operate the installed items. After verifying and testing, the program was copied onto the Raspberry PI 2 memory card.

3.2. Client software

The objective of the project was to create a universal client application to be run both on a traditional PC and on a smartphone with the Android operating system. The purpose of the "Client" application is to remotely control the mobile robot by the operator. The direction choice and other commands are assigned

to respective keys on the computer's keyboard. In the case of the smartphone application, a simple graphical interface has been built, which features push-buttons for controlling the vehicle. The pygame library utilized in the application allows a joystick to be additionally used, but this has not been implemented in the current program version [3]. A characteristic feature of the Python language is the easy exchangeability of applications written in this language between different operating systems or devices [1, 5, 19]. A single code (text file) is created, and then, by compiling it, the interpreter adapts it to a specific system. This immensely facilitates programming. In the case of the "Client" application, this enabled the creation of a kernel common to both operating systems, after which the program was adjusted to the requirements of the Windows and Android operating systems, based on the shared part of the code.

Tab. 3. Description of keys in the pygame library [15].

K_UP	Key „Arrow Up”
K_DOWN	Key „Arrow Down”
K_LEFT	Key „Arrow Left”
K_RIGHT	Key „Arrow Right”
K_ESCAPE	Key ESC

The analysis of the block diagram (Fig. 5) and table 2 shows that the basic job of the 'Client' application is to make a connection with the Server and send to the Server the codes of the commands responsible for performing specific tasks by the robot. Before starting to create the software, a decision was made to write the entire application from scratch. This applied especially to key operation procedures. It turned out, however, that the Python language environment included a ready-made library, called pygame, that was used by game producers. The examination of the library showed that it lent itself perfectly to the 'Client' application being designed. Therefore, it was decided to abandon the original concept and use the ready-made solution. Thanks to the library, the codes of keys pressed by the operator are red out. Key descriptions incorporated in the library (table 3) make it possible to determine, which key has been pressed or released.

For controlling the robot, 5 keys are sufficient: the arrowup, arrowdown, arrow left, arrow right and the ESC keys. The arrow keys are responsible for respective model movements: forward, backward, to the right and to the left. The ESC key terminates the software operation.

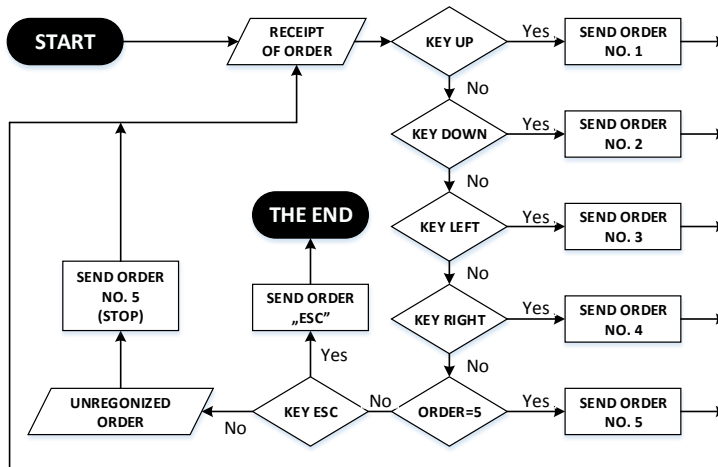


Fig. 5. The block diagram of the application 'Client' [source: own study].

Similarly, as the 'Server' program, the client application requires the declaration of libraries to be used in the further part of the code to be made in the program's heading. Moreover, the Server's IP address and the number of the communication port required for connection have been defined:

```

import socket
import time
import pygame
broadcastIP = '192.168.2.1' # IP server address
broadcastPort = 6666 # Communication port address
  
```

To ensure the smooth operation of the robot, the remote control requires the smallest possible user's response delay. Therefore, the interval within which the user's actions are interpreted and automatically sent to the Server has been set. The time interval is, at the same time, adjusted to the operations to be executed by the Server between the receipt of the commands. Then, the connection socket is created and opened:

```

interval = 0.2 # Command sending interval - 0.2s
regularUpdate = True
sender = socket.socket(socket.AF_INET, socket.SOCK_DGRAM,
socket.IPPROTO_UDP)
# Creating socket (socket)
sender.setsockopt(socket.SOL_SOCKET, socket.SO_BROADCAST, 1)
sender.bind(('0.0.0.0', 0))
  
```

The next steps include the initiation of the declared variables, launching the pygame library and assigning instructions to respective keys.

```
hadEvent = True
moveUp = False
moveDown = False
moveLeft = False
moveRight = False
moveQuit = False
pygame.init()

screen = pygame.display.set_mode([300,300])
pygame.display.set_caption("Robot - Operator")

def operations(events):
    global hadEvent
    global moveUp
    global moveDown
    global moveLeft
    global moveRight
    global moveQuit

    for event in events:
        # Setting variables after aborting by the user
        if event.type == pygame.QUIT:
            hadEvent = True
            moveQuit = True
            ,

        elif event.type == pygame.KEYDOWN:
            hadEvent = True
            if event.key == pygame.K_UP:
                moveUp = True
            elif event.key == pygame.K_DOWN:
                moveDown = True
            (...)
            if event.key == pygame.K_UP:
                moveUp = False
            elif event.key == pygame.K_DOWN:
                moveDown = False
            (...)
```

After configuring the libraries and key actions, starting of the program's main loop follows. Specific commands are assigned to respective key actions: 1, 2, 3, 4 and 5 are assigned to the Server's actions.

```
try:
    print 'Press [ESC] to exit ...'
# Main loop
while True:
```

```

operations(pygame.event.get())
if hadEvent or regularUpdate:
hadEvent = False
driveCommands = ['X']

if moveQuit:           break
elif moveLeft:        driveCommands = '3'
elif moveRight:       driveCommands = '4'
elif moveUp:          driveCommands = '1'
elif moveDown:        driveCommands = '2'
else:
driveCommands = '5' # Sending command 5 - STOP

```

After assigning a specific command, sending it to the Server follows via the connection made previously.

```

sender.sendto(driveCommands, (broadcastIP, broadcastPort))
time.sleep(interval) # Waiting according to interval
sender.sendto('ALLOFF', (broadcastIP, broadcastPort))

```

In line with the employed programming method, the 'Client' program has a modular construction and is written in a universal manner. Similarly, as for the second part of the application, 'Server', its further expansion is possible by writing in successive procedures and functions (e.g. the use of a joystick for controlling the mobile robot's movement).

4. CONCLUSIONS

The developed test stand became a basis for carrying out the analysis of the use of the Python language for the control and management of the operation of an autonomous track-laying mobile robot. The structure and principles of programming in the Python language are similar to those of other programming languages. It enables structural and object-oriented programming, and its syntax is modelled on the C and C++ languages. Its advantage is the cross-platform capability and a huge library of extensions, created by independent programmers. The best examples are the pygame libraries used in the design, created originally to operate keyboards and joysticks in games, and the specialized library for operating the GPIO connector of the Raspberry PI 2 platform. Creating the user's own procedures, functions and definitions is straightforward, and the created code is legible and easy to analyze. The tests of the robot have confirmed the correctness of the programming algorithms used. The robot moves smoothly

and correctly analyzes the environment, in which it moves [20]. The greatest disadvantage and, on the other hand, advantage is the fact that the Python language is an interpreted language. This translates into the size of the code, the requirement for the presence of an operating system and a dedicated compiler, and a lower operation speed compared to applications created using the C or C++ language (compiled languages). In spite of this drawback, the analysis has shown the Python language to be useful for programming mobile robot control systems, especially for users having no extensive programming knowledge [1, 4, 8, 9, 10]. The best evidence for the capability of the Python language is its use by the NASA for controlling the launch of space shuttles and in the Nebula project [15].

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customer, product planning, QFD

*Izabela KUTSCHENREITER-PRASZKIEWICZ**

CUSTOMER ORIENTED PRODUCT PLANNING PROCEDURE

Abstract

One of the most important issues in product planning is to identify customer needs and combine them with product technical and trade characteristics. Identification of customer needs was discussed, and product decomposition method was presented in the paper. The Quality Function Deployment method was suggested to be applied as a product and production process data integration tool, where engineering characteristics of a product are combined with its trade characteristics.

1. INTRODUCTION

One of the strategies adopted by several companies is to manufacture products according to individual customer requirements with low production costs.

Application of computer aided systems supporting decisions on customized product configuration requires identifying attributes which are important from both customer and producer perspective.

Researchers have developed methods which combine customer needs with product characteristics, taking into consideration the production process. Tseng et al. [22] combined virtual prototyping with manufacturing simulation techniques to allow individual customer requirements and production process capabilities of company to be balanced in the design stage. Yao et al. [24–26] proposed a system for a rapid design and simulation of manufacturing systems. In the proposed system, an information model based on part characteristics features was used.

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Cheng et al. presented a structure-based approach to evaluating product adaptability in adaptable design, where they noticed that modular product structure can be used to create a variety of products [2].

Knowledge based-systems, which support decision problems in enterprises, are widely developed, e.g. a knowledge-based system for assembly sequence planning was developed by Hsu et al. [6]. Neural networks NN in supporting decisions in manufacturing process were used by Kim et al. [11], Lai et al. [13] and Sukthomya [21]. Methods useful in product planning and manufacturing were analysed by Quiza et al. [17], Rafiei et al. [18], Sakamoto [20], Xu et al. [23].

The key issues of manufacturing products according to individual customer requirements are:

- Finding product characteristics suitable for a particular customer.
- Product planning procedure - finding or designing products which correspond to given product characteristics.
- Defining resources needed for the manufacturing process.

The proposed customer-oriented product planning procedure can be used as a method of data analysis in knowledge-based systems supporting product configuration.

2. FINDING PRODUCT CHARACTERISTICS SUITABLE FOR A PARTICULAR CUSTOMER

Product characteristics needed by a particular customer can be described on three levels: core part of the product, tangible product and augmented product. Core product refers to the product use and its function. The meaning of core product determines product assortment line. Tangible product characteristics include, among others, quality or style, and determine the type of product item in the assortment line. Augmented product includes warranties, installation, etc. and another services offered in relation with the product.

These three levels of product can be used in the procedure of finding product characteristic suitable for a particular client. The main steps in the proposed product characteristics procedure include:

1. Core product characteristics – basic product function characteristics.
2. Tangible product characteristics – secondary product function characteristics.
3. Augmented product characteristics – services added to the product, trade characteristics.

Product function identification and improvement can be supported by value engineering. The basic questions which helps to identify the function are: What does the product do? What must it do? What should it do? What could it do? What must it not do? Value engineering was applied for instance by Cook et al. [4].

In product function identification, Kano's model (fig. 1) can be used. Kano's model divided product characteristics into the following categories [2]: must-be requirements, one-dimensional requirements, attractive requirements, indifferent requirements and reverse requirements. Must-be requirements are focused on customer buying decision. If the attributes are not offered, the product will not be bought at all. These attributes are necessary for a customer and create core product. One-dimensional requirements influence customer satisfaction. If this type of product attributes are offered on a high level, customer satisfaction will increase. Attractive requirements are not expected by customers. This kind of attributes cause customer satisfaction. If this kind of attribute is not offered, customer will not notice it. Indifference requirements – customer is not interested in these attributes. Reverse requirements – customer is dissatisfied if the attribute is offered, a lower level of this attribute causes customer satisfaction.

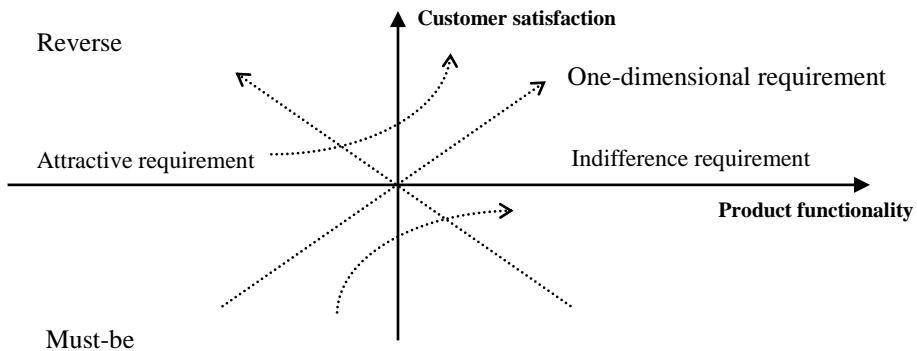


Fig. 1. Kano's model of customer satisfaction [source: on the basis of [2]]

3. PRODUCT PLANNING PROCEDURE

The concept of made-to-order (MTO) product assumes that customers influence product design. In many cases product changes bring about production process changes. Some product changes require tools which have not been used until now in the production process. The question is how product changes influence production cost and product delivery time, and how that calculation should be performed. MTO product planning requires: establishing the type of product changes, limit of acceptable changes (e.g. product dimensions, materials, functions), product reliability assessment and production process capability assessment. The procedure of product planning was presented in fig. 2.

In the proposed procedure, the concept of three level product characteristics was applied.

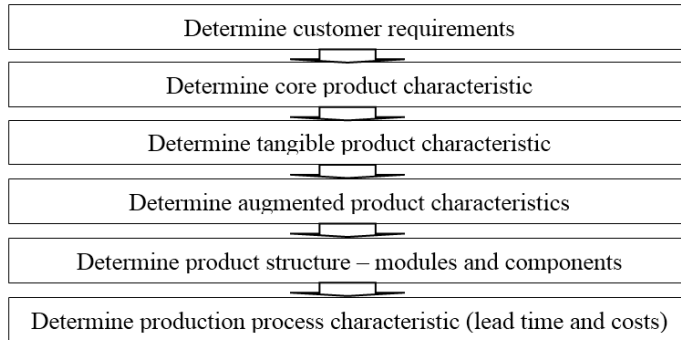


Fig. 2. Product planning procedure [source: own study]

Customer requirements determination can be carried out with the use of the QFD method. QFD is used as a method which helps increase customer satisfaction. Jariri et al. [8] applied QFD for optimizing customer satisfaction focused on target costs. Many authors link QFD with other methods, Baier et al. [1] links Quality Function Deployment and Conjoint Analysis for new product design, Chou [3] joins NN with QFD in conceptual design. Poel [16] has also discussed some methodological problems in QFD.

QFD has been applied in many industrial branches in a wide range of use. QFD helps to specify product features which are important for the customer and designers, as well as for production engineers.

The relation between main features important for the customer, designer and production engineers can be presented in QFD series of matrices. The first one represents the relation between customer requirements and product characteristics (fig. 3). The second one describes the relation between product characteristics and product parts. The third QFD matrix provides information related to the production process. The fourth one provides information related to the production process parameters [7, 19].

What?		How?		Product characteristic			Importance
		Attributes	Value	p_{mk1}	p_{mk2}	...	
Customer requirements	f_1	f_{11}^w	c_{11}	c_{12}		c_{1k}	
	f_2	f_{22}^w	c_{21}	c_{22}		c_{2k}	
	f_n	f_{n2}^w	c_{z1}	c_{z2}		c_{zk}	
	Target level of product characteristic			p_{mk1t}^{woz}	p_{mk2t}^{woz}		p_{mkzt}^{woz}

Fig. 3. QFD matrix [12]

In the QFD matrix presented in fig. 3 above, “ c_{zk} ” denotes a correlation between customer requirements and product characteristics and takes value 1, 3 or 9, where 1 means a weak correlation, 3 means a medium correlation and 9 means a strong correlation. The correlation between product characteristic on the matrix roof can be positive, denoted by “+” or negative, denoted by “-”.

The next step in the proposed product planning procedure is focused on product structure determination. Fan et al. [5] proposed a product structure which includes: basic module (an indispensable module for forming a product), must – selected module chosen to create a customised product, may – selected module – a special supplementary and customized module.

Researchers have focused on different aspects and methods supporting product configuration. Ming et al. [15] presented gaps analysis in the existing concepts supporting product configuration:

- collaborative design portal – lack of design of user friendly interfaces to enable real time collaboration,
- configurable design – lack of systematic ontology and processes on product configuration design,
- modular design – lack of systematic technology to represent, identify, reuse modules in new product development,
- platform-based design – lack of systematic technology to represent platform design,
- product knowledge management – lack of systematic way to represent, capture, organize, share, apply, create the design knowledge,
- lifecycle evaluation and optimization – lack of systematic way to evaluate life cycle efficiency at an early design stage.

Customer needs identification is the first step of product configuration. Customer needs can include engineering characteristics, as well as trade characteristics. Engineering characteristics include product attributes determining product usefulness, which include technical product attributes, e.g. power, speed. In turn, trade characteristics can include e.g. product price, warranty and delivery time. Customer product characteristics should be transformed to the product characteristics made by producers and product structure comes from these characteristics. One of the concepts useful in creating product structure is modular design.

In MTO product modularity is a useful concept in modelling customized product configuration. The concept of modularity is focused on designing products that can respond rapidly to market needs and allow the changes in product design in a cost-effective manner. Modularity can be applied to the design process to build a modular product and a modular manufacturing process [10].

Modular products may shorten product-development time and help to introduce new product variants at reduced costs [14].

Modularity in product and process design is focused on reducing the range of product parts and manufacturing processes variation. According to this concept, product variants use common units (fig. 4).

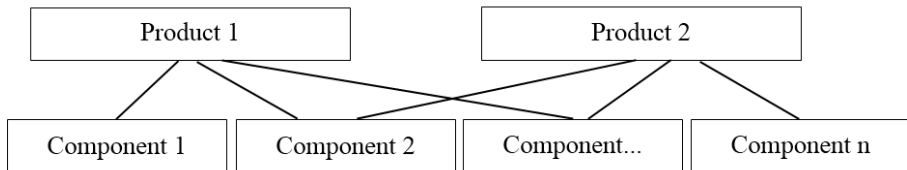
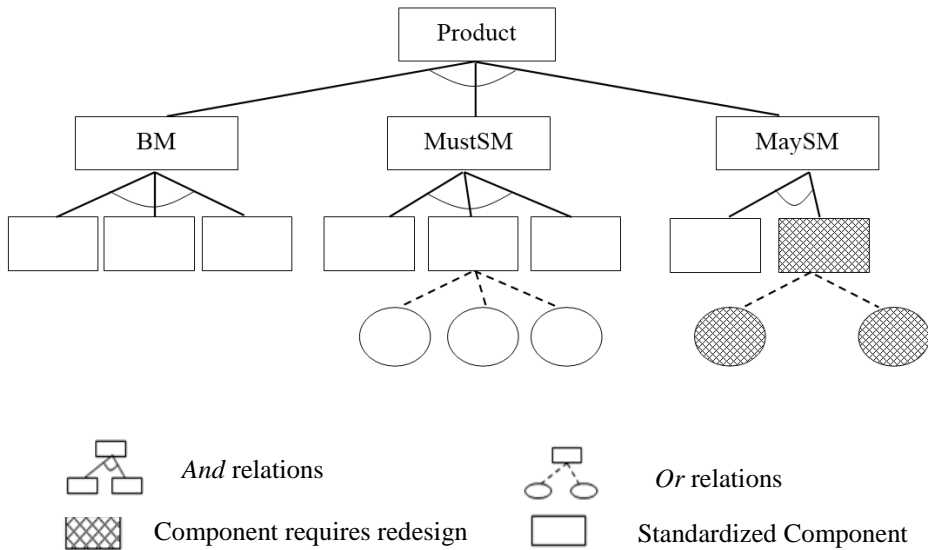


Fig. 4. A structure of product family [source: on the basis of [5]]

Product structure should help to increase external diversity of products – diversity of configured products, and reduce internal diversity of product.

Modular product structure can be presented with the use of a decomposition tree. Jiao et al. [9] proposed product decomposition tree which applies two types of nodes and two types of edges. A squared node means a product component, an oval node means an attribute characterising a product component. Edges link nodes in two manners, as and/or relations.

The general structure of a modular product was presented in fig. 5. In the presented product structure, some components are basic, which means they are indispensable module for forming the product; some of them are selected to create a customised product, and some are special supplementary and customized modules which need to be redesigned.



BM – basic module, MustSM – must selected module, MaySM – may selected module.

Fig. 5. Modular product structure [source: on the basis of [9]]

5. AN EXAMPLE OF PRODUCT PLANNING

Product planning is focused on finding the right moto reducer components. A customer defined main product requirements which were divided into categories according to Kano's model. Each customer requirement was assessed in the right part of the QFD matrix (fig. 6) according to following scale:

- 1 – must – be requirements,
- 2 – one – dimensional requirements,
- 3 – attractive requirements,
- 4 – indifferent requirements,
- 5 – reverse requirements.

What?		How?		Product characteristic					
		Attribute	Value	Weight	Size	Stage_no	Costs	Lead time	Import.
Customer requirements	Core product	Type of use	feeder device	3	3	3			1
	Tangible product	Power	3 kW	3	3	3	3		2
		Speed	3 m/s	3	3	3	3		2
	Augmented product	Price	low	3	3	3	9		5
		Delivery time	2 weeks	3	3	3	9	9	5
	Target level of product characteristic				120	230	1	250	50

Fig. 6. A QFD matrix for moto reducer [source: on the basis of [12]]

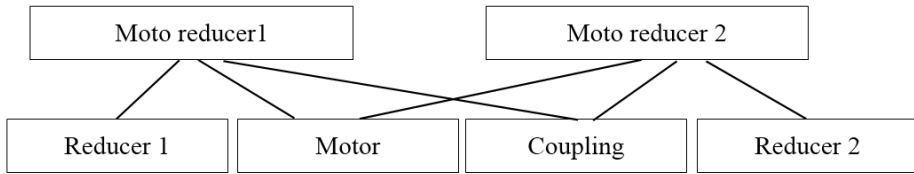


Fig. 7. Structure of product family [source: own study]

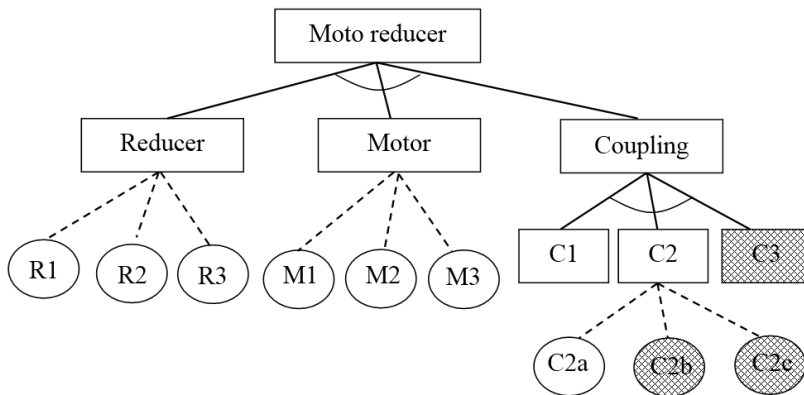


Fig. 8. Modular product structure [source: on the basis of [12]]

What?		How?		Product structure		
		Attribute	Value	reducer	motor	coupling
Product characteristic	Weight	120	9	9	9	
	Size	230	9	3	3	
	Stage_no	1	9			
	Costs	250	9	9	3	
	Lead time	50	9	9	9	
Part type			R1	M2	C3	

Fig. 9. A QFD matrix for toothed gear [source: on the basis of [12]]

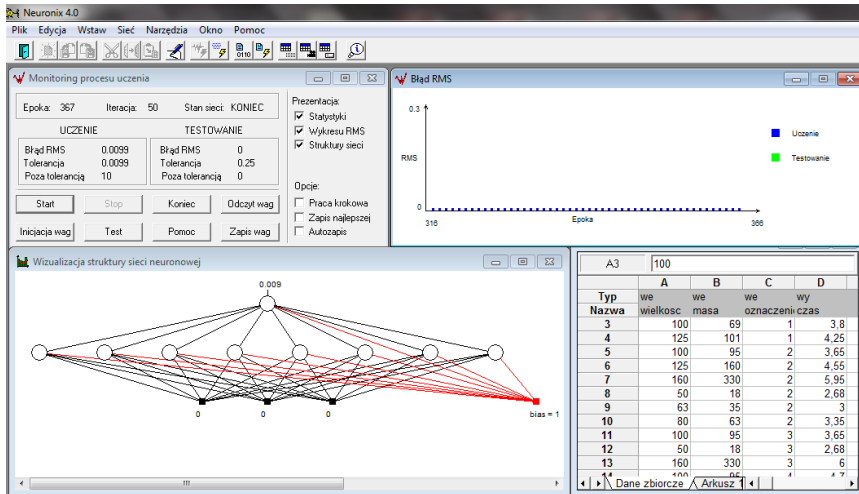


Fig. 10. NN learning process [12]

Structure of the product was presented in figs. 7 and 8. The QFD matrix presented in fig. 9 helps to find the right product components.

The data related to time consumption estimation regarding product structure change was made with the use of NN. The learning process of NN and result of data modelling were presented in fig. 10 [12].

6. CONCLUSION

The presented Kano's model of customer requirements can be used as a base of customer requirements evaluation in the QFD method. Application of graphs in product structure analysis helps in product configuration and reusing product components. The proposed product planning procedure is useful in product attributes identification needed by customer as well as attributes identification which characterise product and manufacturing process. The presented approach can be useful in applying computer technology in systems supporting product configuration decisions. Data analysis and attribute definition which emerge from the presented methodology can be applied in training set development, which is useful in data mining technique, like neural network.

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observatory, competitive intelligence, decision-maker, Yii, DWH

*Percy OKAE**, *Amos DAVID***

A YII-POWERED WEB APPLICATION TO ASSIST DECISION-MAKERS IN MUNICIPAL SOLID WASTE MANAGEMENT

Abstract

This paper adopts the concepts of observatory and competitive intelligence (CI) to model a system that will generate better insights for decision-makers in the solid waste industry. The first part of this work is to design and develop a data warehouse (DWH) of solid waste statistics using data assembled from disparate sources. Our methodology of design is the entity relationship diagram (ERD) and our implementation tool is MySQL running on phpMyAdmin. The second part of our work will be to turn our developed DWH into a Web application using the Yii PHP component framework. Our findings indicated that the application of both concepts of observatory and CI lead to better insights for decision-makers and hence better organizational performance.

1. INTRODUCTION

Since our system is supposed to be a Yii-based Web application, we use *PHP 5.6.3* and *MySQL 5.6.21* database application for the development of the Web site. The source from which we acquired all these required software tools is the XAMPP solution stack, which is an open-source, obtained from <http://www.apachefriends.org/en/xampp-windows.html>. Also our Web server will be *Apache httpd 2.4.10* and our *webroot* directory will be `C:\xampp\htdocs\mswproject/`.

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1.1. Why observatory and CI?

There is already a large body of literature on the management of municipal solid waste (MSW) using various design concepts. We note that CI has over the years been deployed in disciplines such as *wind turbine manufacturing*, *automobile manufacturing*, *software development*, *aeronautics*, and *pharmaceuticals* etc. For instance, by the aggressive application of CI techniques, Microsoft Corporation has been able to eclipse competitive products from competitors in the software industry. Products such as *WordPerfect*, *Lotus 1-2-3*, and *Netscape Navigator* have all been outdone by respective equivalent products namely; *MS Word*, *MS Excel*, and *Internet Explorer* by the determined deployment of CI as a prioritized unit within Microsoft Corporation. However, the application of the CI process in the field of solid waste management remains vastly unexplored.

What do we therefore mean by the term CI? According to SCIP (2012) [12], CI is the legal and ethical collection and analysis of information regarding the capabilities, vulnerabilities, and intentions of business competitors. Van Brakel (2005) [10] also defines CI as “*a business discipline that is used by companies and countries alike as a means to improve competitiveness by making better use of information.*” There are so many definitions given by various authors but they all invariably mean the same thing. The key thing is to ensure that the practice is legal and ethical as CI is not espionage.

An observatory is basically a facility which houses a cluster of equipment which contains a repository of data mainly for research purposes in fields such as astronomy, meteorology, and other natural phenomena. In our case, we simply mount our observatory in the study area as and when needed and collect data through observation.

2. METHODOLOGY

We first installed XAMPP which is a free and open source cross-platform Web server solution stack which contains all the tools required for this study. The word XAMPP is an acronym where:

- X means cross-platform;
- A means Apache;
- M means MySQL;
- P means PHP; and
- P means Perl.

Subsequently, we build the shell of our Web application using the *yii* *webapp* tool from the command line. Figure 1 below shows the shell of the Web application consequently generated and customized to display dynamic content as well as the name given to the Web application using the Yii framework.



Fig. 1. A screenshot displaying the homepage edited to display current datetime and last login time [source: own study]

The architecture of the proposed framework showing the CI inputs into the observatory through the DWH and finally to the decision point for decision-makers is shown in Fig. 2 below.

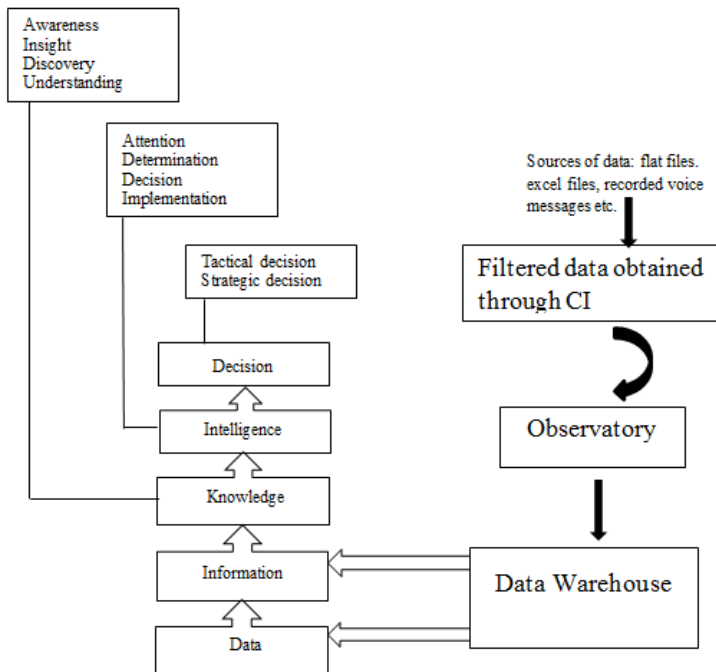


Fig. 2. Architecture of framework of research showing the crucial CI and observatory stages [source: own study]

2.1. Data Warehouse Design Approach

In our design, we adopt the Third-Normal Form (3NF) Data Model as against a Dimensional Data Model or a combination of both for our data warehouse [13]. The benefit of adopting a 3NF ERD model is that it will enforce a “Single View of the Truth”, something not possible with a Dimensional Model.

In our case, the application server will be MySQL DBMS which will host the data warehouse. Subsequently, we will build the Web application using the Yii PHP component framework.

2.2. Data model

The modeling of data in this write-up will be done using ER modeling. We submit that is the best schema to use as it helps a lot in avoiding redundancy of data [6, 7]. We also affirm that the concept of entity-relationship diagram (ERD) — developed by Chris Data, Ted Codd (1970) [4] and Chen (976) [5] — is the option that is most suitable for this design since it works very well with a relational DBMS such as *MySQL*.

We want to design the warehouse to strictly enforce what the operational database does enterprise-wide. The end result of E-R modeling is the E-R diagram (ERD), a graphical representation of the logical structure of a database [1].

2.3. Implementation of the physical DWH

The next stage is the design of the physical DWH in phpMyAdmin using MySQL. XAMPP includes phpMyAdmin which is an open-source, browser-based tool for managing MySQL database servers.

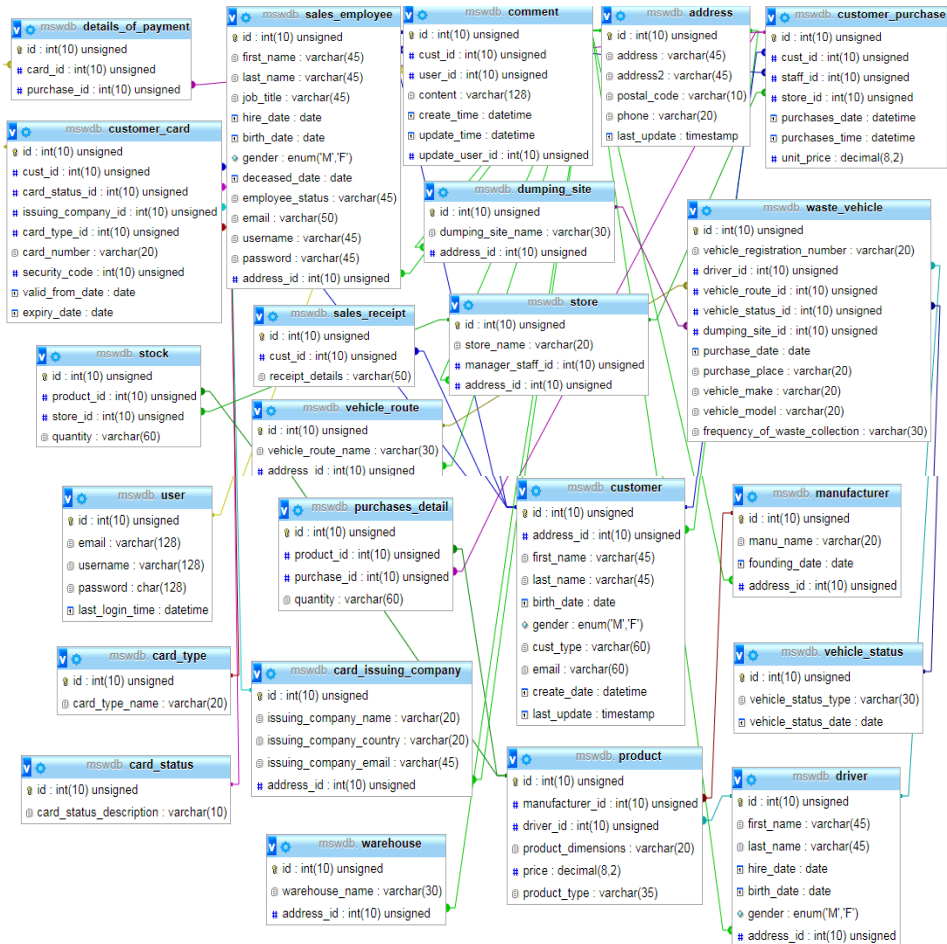


Fig. 3. The physical implementation of the DWH for MSW management built using MySQL running on phpMyAdmin as the UI [source: own study]

2.4. Design of the CI process

Our research methodology is both qualitative and quantitative by approach. Some argue, however, that the qualitative approach is more interesting. Silverman (2010) [11] argues that the qualitative research method is more interesting because of the subjectivists' perspective which always looks for the experiences, views and opinions of people. Miles and Huberman (1994:1) [9] have also posited that words tend to have more impact on people than numbers would if possible. The objective is to impress on managers the contribution that the integration of CI into the operations of the organization can make to better decision-making. Decision-makers will need reports as well as charts to understand

metrics better and so there is a justification for both a qualitative and quantitative approaches. CI as matter of fact is a unit that supports sales and marketing functions of an organization and so it is always difficult to quantify it in terms of revenue. However, its impact is mainly qualitative and this is time-tested and proven.

2.4.1. Data Collection

The data collection technique involved in-depth interview sessions and observations we personally made within our study area with regards to solid waste management.

3. PRESENTATIONS AND DISCUSSION OF RESULTS

3.1. Responses on costs of solid waste containers surveyed on the market

We surveyed 95 residents within randomly selected addresses in the Adentan municipality of our study area about their concerns with regards to the cost of the solid waste containers they need to store their domestic waste products. The variety of responses from these respondents indicated that the costs were also a factor in the poor state of solid waste management within these areas. A total of 55 % of our respondents agreed that the waste bins were either *very expensive*, *expensive* or *not affordable* as shown in Fig. 4.

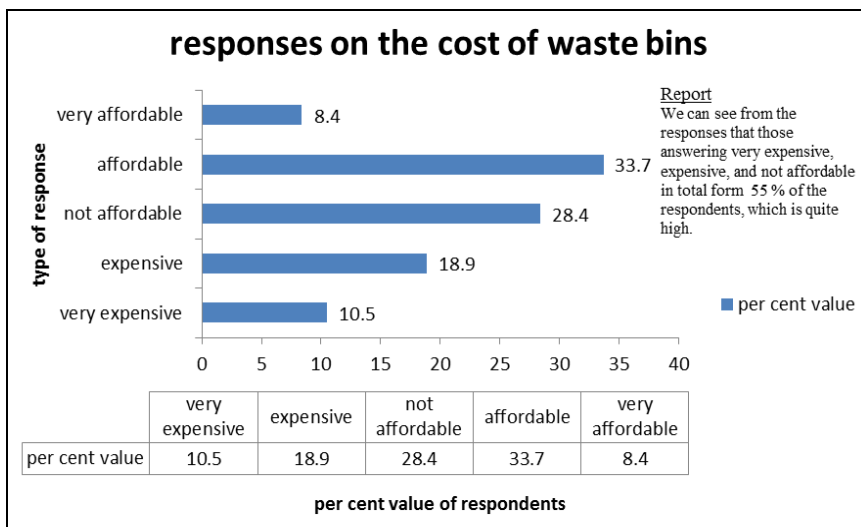


Fig. 4. Chart showing responses of residents on the cost of waste bins [source: own study]

3.2. Responses from selected residents within the study area

Figure 5 below shows the responses we also obtained from a random sample of 43 residents within our study area concerning the general waste management situation. Here 41.9 % of respondents said the situation was average. This is indicative of the fact more room is there for improvement in terms of the way and manner things are done now.

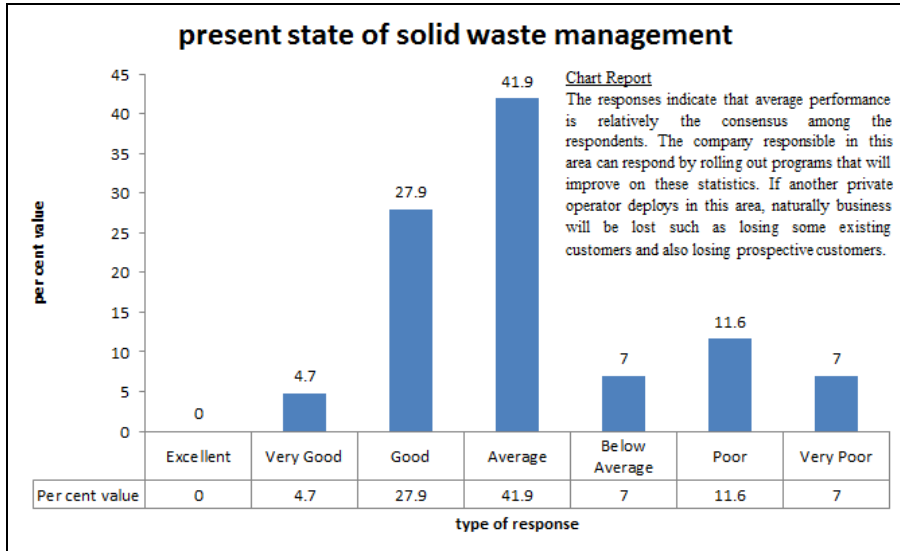


Fig. 5. Chart showing the per cent value of responses from residents of the study area concerning the state of sanitation in their community [source: own study]

3.3. Observations made with regards to times of domestic waste collection

Figure 6 displays the times that assigned solid waste-carrying vehicles arrived to carry domestic waste to the dumping site during the 60-day window during which we mounted our observatory to see things first hand for ourselves. We noted that the regular times of solid waste collection by the waste management company was not strictly followed and there were also days when even the trucks did not turn up.

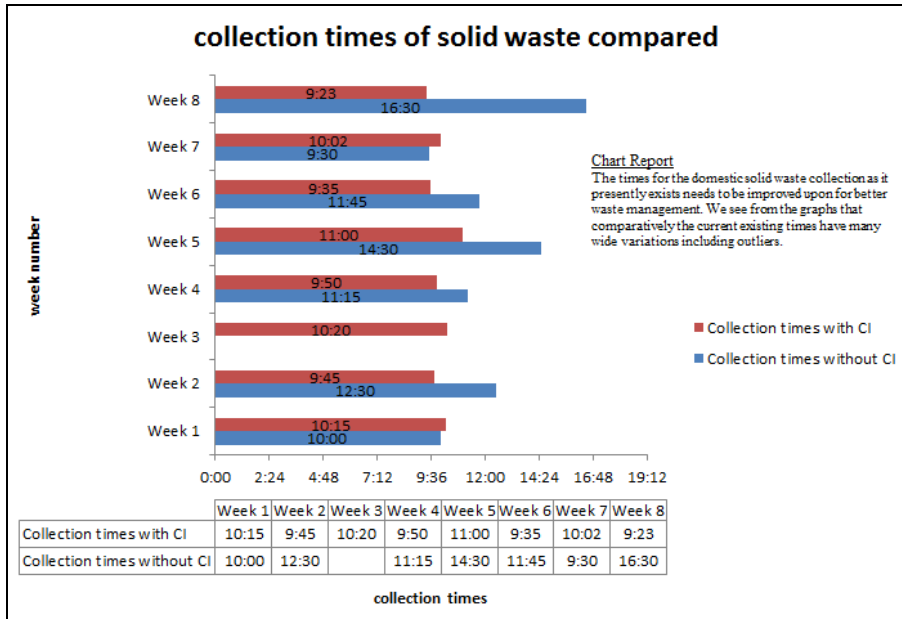


Fig. 6. Graph comparing the times of MSW collection using CI and without CI [source: own study]

3.4. Implementation of the Yii-powered Web application

A typical Web page of a customer of the waste management company who has purchased a waste-carrying bin is shown in Fig. 7 below. From the results obtained through the CI process, this very customer for instance, could benefit from decision-makers in the waste management company if they do a critical analysis and up their game such as factoring the cost of the waste bins into their business plans to attract new customers or retain existing ones.



Fig. 7. A screenshot of the view of the details of a customer of the waste management company [source: own study]

4. CONCLUSIONS

We have modeled a Yii-powered Web site of a data warehouse meant to assist management in decision-making of MSW management. For a fact, a DWH is the business analyst's dream of having all the historical data or information about a specific task assembled in one place. This is exactly what we have done. We want to contribute to the effective management of MSW by way of the production of intelligence acquired through the processing of disparate sources of information. A major finding of this research work is that the frequency of waste collection in various communities within the study area is not good enough. The improvement we expect can be achieved if the concept of CI is fully integrated into the core business of the organization.

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turning, shaft with low rigidity, numerical simulation studies

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NUMERICAL SIMULATION STUDIES ON THE PROCESS OF MACHINING OF SHAFTS WITH LOW RIGIDITY

Abstract

The paper presents a computer program developed for the determination of the basic dynamic characteristics of the process of machining, numerical simulations of the dynamic system of the process of machining, and graphic presentations of the numerical simulations performed. Results of simulations of the runs of time and frequency characteristics of the process of machining with variable machining parameters are presented. High goodness-of-fit of the model with the actual process of turning was achieved.

1. INTRODUCTION

The knowledge of the technical behaviour of machined parts during the production processes is very important both for the technologists and also for the manufacturing systems design purposes [3, 4, 7]. Therefore both modelling of the machining processes and the numerical studies are necessary and valuable [2, 12]. For the purpose of provided research in the area of low-rigidity shafts machining the program MATMOD was developed. The program allows the determination of the conditions and the basic dynamic characteristics of the machining process, numerical simulation of the dynamic system of the machining process, and graphic presentation of the characteristics of the numerical simulations performed [1].

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The paper presents the result of simulations of the runs of time and frequency characteristics of machining process performed at various values of machining parameters. The tests were performed for a shaft of steel C45, with dimensions of $l_p = 280$ mm, $d_p = 40$ mm. The variable input parameters were the rotation speed $n_p = 700, 1100, 1500$ rev/min; feed $f = 0.1, 0.25, 0.5$ mm/rev; depth of machining $a_p = 1, 2, 3$ mm.

Based on the experimental study of the process of machining and on the results obtained in the simulation studies, conducted at the same parameters of the machining process that were applied in the experiment, a comparison was made of the experimental and simulation results. The value of relative deviations between the experimental data and those from the simulations, δ (%), equalled 9.61%, which indicates very good fitting of the model with the actual run of the process of turning. The results obtained can be used as a starting point for further research in the area of design of systems of automated adjustment.

2. CHARACTERISATION OF COMPUTER PROGRAM MATMOD

For the needs of the study of the characteristics of the dynamic system the computer program *MATMOD* was developed [1, 10, 11].

The program realizes the following functions:

- determination of the conditions of the machining process after entering the parameters, of the machine tool, the object machined, and of the technological process,
- calculation, on the basis of models of the dynamic system of the machining process, of the basic dynamic characteristics (including operator transmittance), cutting force responses to step-wise change in feed rate, and frequency characteristics: amplitude and phase.

The program allows the performance of numerous numerical simulations of the dynamic system of the process of machining. It supports three kinds of fixing of the machines component, that have a significant effect on the final result of the computations: in lathe centres, in a chuck and a centre, and in two chucks. Depending on the kind of fixing, the program determines the maximum flexibility of the machined component in the radial direction. The program accepts input data for machined components differing in length. An additional advantage of the program is the possibility of defining the properties of the material machined by adding e.g. the values of E and R_m . Other input data for the computation process include also the values of the machine tool flexibility in the direction of coordinates X, Y and Z , as well as the depth of machining, feed rate, tool cutting edge angle κ (on the range from 45^0 to 90^0) and the rotation speed of the machined component n_p (in the range from 100 to 2000 rev/min). After entering all the input data the program performs the computations.

The first to be calculated are the values of forces F_f , F_c and F_p , and then the amplification coefficients of the machining process m_x , m_y , and m_z with a change of feed rate and machining depth (these values can be treated as interference). The coefficient of relative dynamic stiffness B is determined, and then the operator transmittance in control, corresponding to the presented conditions, and the amplification coefficients of the component K_{ox} , K_{oy} , K_{oz} and retardation τ . Therefore, the maximum value of coefficient B and operator transmittance at interference are determined again [10,11]:

$$G_{v_f g_i}(s) = \frac{\Delta F_i(s)}{\Delta v_f} = \frac{m_x h_{xx} G_\tau(s)}{s[(T_c s + 1)(T_{us}^2 s^2 + 2\xi T_{us} s + 1) + B_1 G_\tau(s) + n_y h_{yy}]}, \quad (1)$$

where: $G_\tau(s) = 1 - e^{-s\tau}$,

$$B_1 = m_x h_x + K_{\kappa_r} m_y h_y.$$

Coefficients K_{bx} , K_{by} , K_{bz} and the values of coefficient B and retardation τ are also calculated.

In the case of control, the operator transmittance of the approximated object is determined as follows:

$$G_o(s) = \frac{\Delta Y_o(s)}{\Delta v_f(s)} = \frac{K_o}{(T_1 s + 1)(T_2 s + 1)}. \quad (2)$$

After determining the operator transmittance, coefficients K_{ox} , K_{oy} , K_{oz} and time constants T_1 and T_2 are determined.

The final stage of the computational part of the program is the determination of the operator transmittance of the object at a variable material allowance $b(s)$, treated as an interference. In the initial phase the object transmittance is determined in accordance with specific rules. In the case of changes of the material allowance $b(s)$ the operator transmittance of the object can assume the following form [10,11]:

$$G_{bFi}(s) = \frac{\Delta F_i(s)}{\Delta b_i(s)} = \frac{K_{bFi}(s)(1 - e^{-s\tau})}{s\tau[1 + B(1 - e^{-s\tau})]}, \quad (3)$$

whereas, coefficient B is determined from the relation:

$$B = \frac{m_x h_{xx} + K_{\kappa_r} m_y h_{yy}}{1 + n_y h_{yy}}. \quad (4)$$

The program permits also the calculation of the values of elastic deformations relative to coordinates X , Y , Z and of the coefficients K_{ab} : K_{abx} , K_{aby} , K_{abz} . Equivalent values of the time constants T_1 and T_2 are determined, the coefficient of object amplification K_o and coefficient B . The last to be determined are the stabilised output value Y_{ust} and the maximum relative error of approximation.

The program permits also the presentation of graphic characteristics of numerical simulations.

After starting the program, we need to enter the parameters of the machining process, the geometric parameters and the properties of the machined component. The limit values of the parameters (the minimum and the maximum values) are entered at the moment when the question about the value of a given parameter is displayed on the screen. The user can choose between the program options: calculation of response to unit step of feed and calculation of frequency characteristics. The graph of the amplitude frequency characteristics presents the relation of module $A(\omega)$ of spectral transmittance $G(j\omega)$ in the function of circular frequency $\omega = 2\pi f$, and that of the phase frequency characteristics – $\varphi(\omega)$ in the function of circular frequency $\omega = 2\pi f$.

In the case of response to unit change of longitudinal feed, a graph of changes of machining force in time is displayed on the screen, for the accurate and the approximated models. Discrete values of the response (40 points) can be saved in the form of a table. It is also possible to save the complete information on data entered and on the results of computations of the parameters of the machining process. The program permits also to make copies of the graphic screen with responses to unit step of longitudinal feed.

If we select the option of calculation of the amplitude and phase frequency characteristics, graphs of the amplitude and phase frequency characteristics of the accurate and approximated models will be displayed on the screen. Discrete values of the characteristics (20 points) can be saved in the form of a table. The frequency characteristics are presented in a semi-logarithmic scale. It is also possible to print a copy of the screen with the amplitude and phase characteristics.

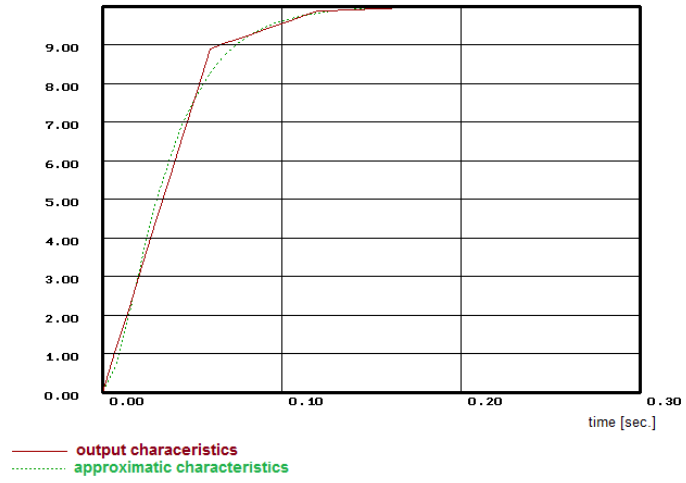


Fig. 1. Output time-characteristics (accurate and approximated) [source: own study]

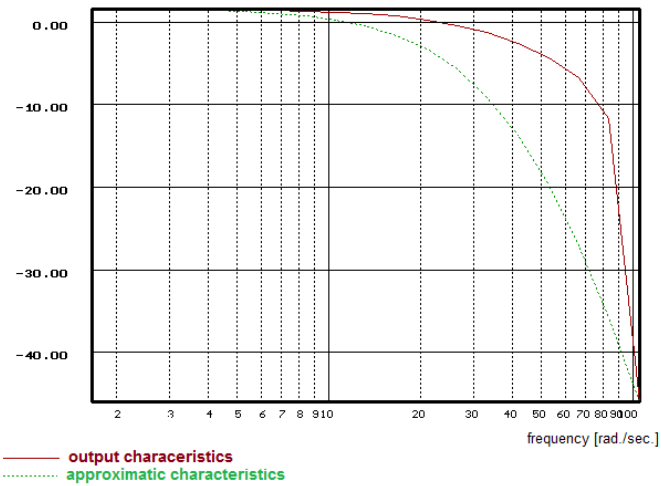


Fig. 2. Amplitude-frequency characteristic [source: own study]

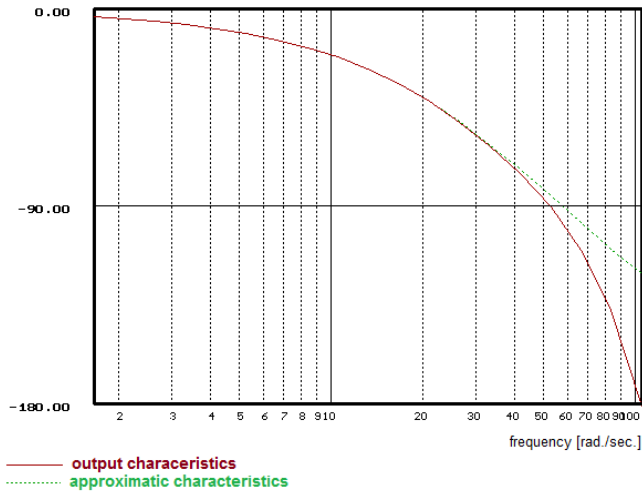


Fig. 3. Phase-frequency characteristic [source: own study]

Examples of results of numerical studies performed in the program *MATMOD 1* are shown in Figs. 1, 2, 3 which present the process of machining at various parameters in the form of suitable characteristics.

3. NUMERICAL SIMULATION STUDIES ON THE DYNAMIC SYSTEM OF THE PROCESS OF MACHINING

Simulations of the runs of time and frequency characteristics of the process of machining were conducted at various values of machining parameters.

The tests were performed for a shaft of steel C45, with dimensions of $l_p = 280$ mm, $d_p = 40$ mm. The variable input parameters were the rotation speed $n_p = 700, 1100, 1500$ rev/min; feed $f = 0.1, 0.25, 0.5$ mm/rev; depth of machining $a_p = 1, 2, 3$ mm.

Results of simulations of the process of machining performed with the use of the program *MATMOD* are presented in graphic form in Figs. 4–8.

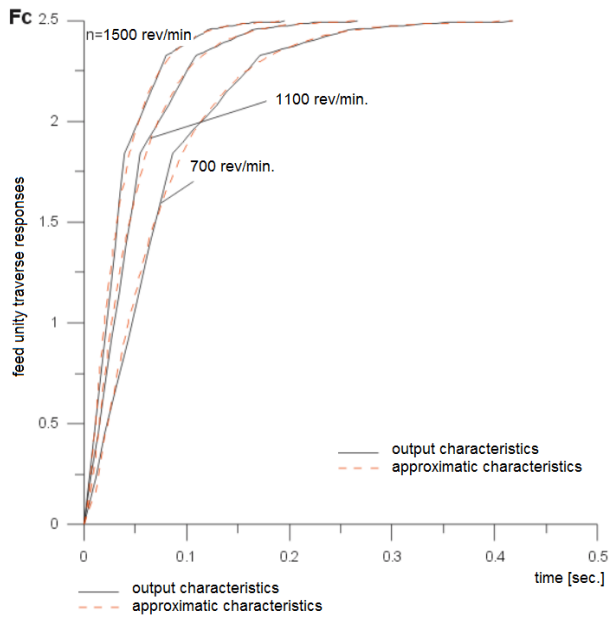


Fig. 4. Machining force responses to unit step of feed at various rotary speeds [source: own study]

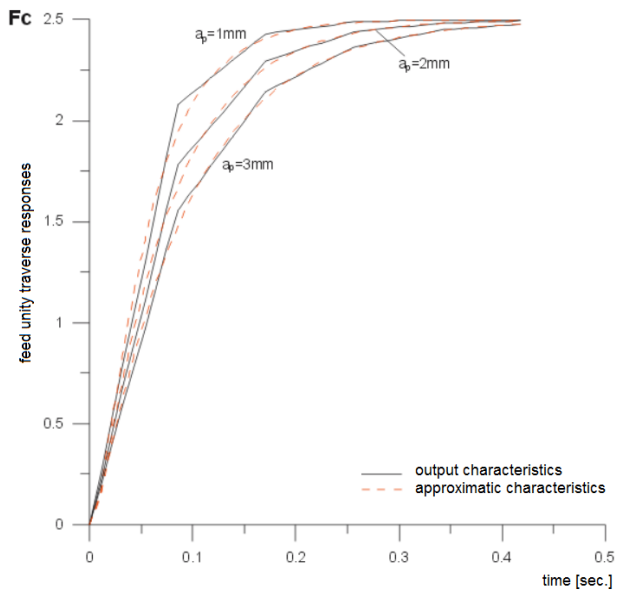


Fig. 5. Machining force responses to unit step of feed at various thicknesses of machined layer [source: own study]

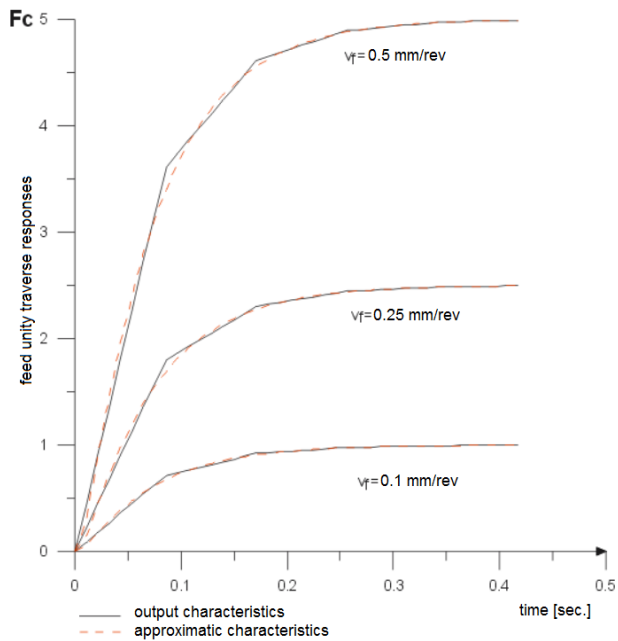


Fig. 6. Machining force responses to unit step of feed at various speeds of machining [source: own study]

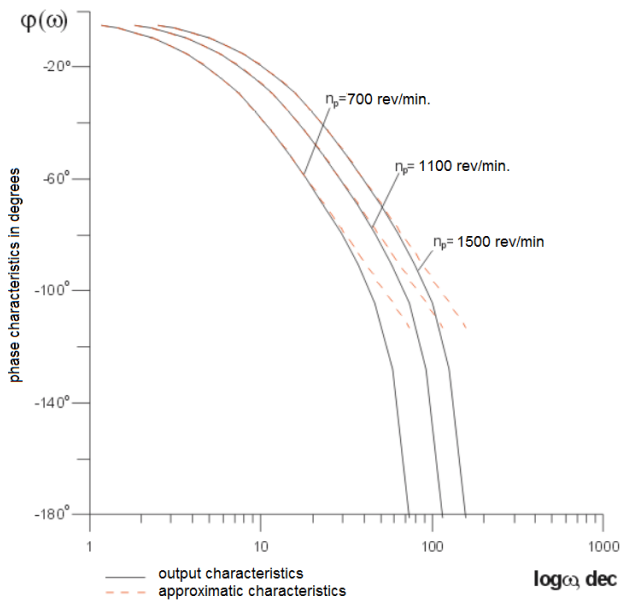


Fig. 7. Phase-frequency characteristics of machining process at various rotary speeds of machined component [source: own study]

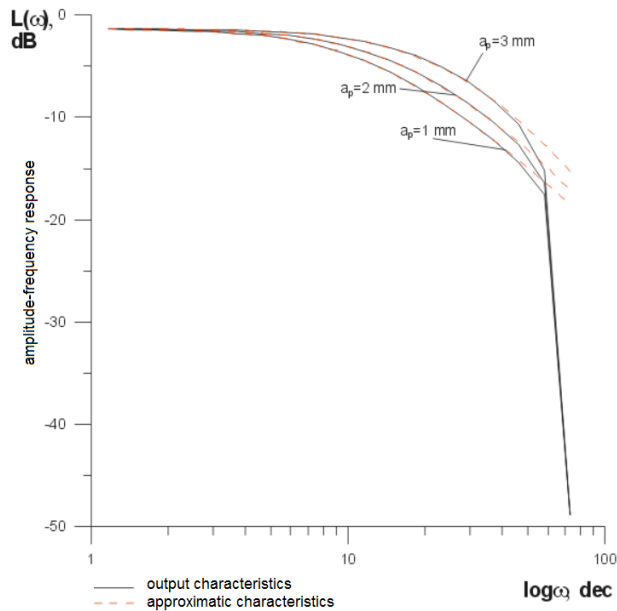


Fig. 8. Amplitude-frequency characteristics of machining process at various thicknesses of machined layer [source: own study]

Machining force responses at step-wise changes of feed rate, with varied conditions of the process of machining, are presented in Figs. 4–6. The phase-frequency and amplitude-frequency characteristics of the process of machining are presented in Figs. 7–8.

4. ANALYSIS OF RESULTS OF SIMULATIONS

Based on the simulations conducted within the scope of the study it was observed that:

- a change of rotary speed causes a change in the time of stabilisation of the transient run,
- a change of the thickness of machined layer causes a corresponding change of response to unit step of feed, but at constant time intervals,
- a change of feed rate causes a change in the values of machining force at steady state in response to unit step of feed,
- changes in the phase characteristics are the most observable during changes of rotary speed, while in the case of changes of feed rate and thickness of machined layer the differences are small,
- changes in the amplitude characteristics can be observed mainly in the case of changes in the thickness of machined layer.

Based on the results of experimental tests of the process of machining [6, 8, 9] and on the results of the simulations, conducted at the same parameters of the machining process as those applied in the experiment, a comparative table of the experimental and simulation results was compiled (Tab. 1). Column 1 gives the successive numbers of experimental tests conducted on a test stand equipped with a lathe, measuring instruments and computer system for recording the changes of the parameters in the course of the experiment. Columns 2–7 specify the parameters of the process of machining applied in the successive experiments. Column 8 lists the time constants of the process, obtained in the experiment, and column 9 – the time constant calculated on the basis of the developed mathematical model. Column 10 gives the relative error of determination of the time constant on the basis of the model.

The experimental transition characteristics were approximated with the expression:

$$F_c(t) = F_{c0} [1 - \exp(-t/T_{1e})]$$

where: F_{c0} – determined value of an output value or of its gain,

T_{1e} – equivalent time constant, determined on the basis of experimental transition run as the time after which an output value or its gain attains the level of 0.63 of the value in its steady state.

The values of T_{1e} from the experiment were compared with model-calculated values T_{1p} , defined as the time at which the calculated transition characteristic of the model, described by the relations presented above, attains 0.63 of the steady value.

Based on the values of relative deviations δ (%) obtained between the experimental data and data from the simulations, a mean value of 9.61% was determined. In the case of such a small value, the divergences between the time constants of the model and the results of the experiment indicate a good fit of the model to the actual run of the process of turning. This fact can be used a starting point for further research in the area of design of automatic adjustment systems.

Tab. 1. Parameters of machining versus the calculated and experimental time constants [source: own study]

Item	τ , s	κ_r	v_c , m/s	a_p , mm	a	F_{c0} , N	T_{1e} , s	T_{1p} , s	δ , %
1	0.48	45	0.8	2.0	0.2	900	0.59	0.55	7
2	0.48	45	0.8	3.0	0.2	1380	0.7	0.625	11
3	0.375	45	0.85	1.0	0.2	480	0.3	0.3	0
4	0.375	45	0.85	2.0	0.25	1140	0.46	0.43	7
5	0.375	45	0.85	3.0	0.2	1400	0.55	0.48	13
6	0.24	45	1.3	1.5	0.25	855	0.23	0.215	7
7	0.24	45	1.3	2.0	0.25	1150	0.34	0.28	18
8	0.24	45	1.3	3.0	0.2	1370	0.36	0.31	14
9	0.12	45	1.6	1.5	0.2	730	0.12	0.13	-8
10	0.12	45	1.6	3.0	0.2	1470	0.18	0.161	11
11	0.095	45	1.65	1.0	0.2	475	0.08	0.076	5
12	0.095	45	1.65	3.0	0.2	1475	0.15	0.13	13
13	0.095	45	1.65	5.0	0.1	1180	0.2	0.19	5
14	0.075	45	1.67	1.0	0.2	470	0.06	0.064	-7
15	0.075	45	1.67	2.0	0.2	981	0.11	0.09	18
16	0.075	45	1.67	3.0	0.2	1430	0.12	0.105	5
17	0.048	45	1.69	1.0	0.2	390	0.04	0.04	0
18	0.048	45	1.69	3.0	0.2	795	0.072	0.065	10
19	0.48	90	0.9	1.0	0.25	610	0.3	0.38	-26
20	0.48	90	0.9	2.0	0.25	1200	0.42	0.43	-2
21	0.19	90	1.33	2.0	0.25	1100	0.18	0.17	6
22	0.19	90	1.33	5.0	0.1	1270	0.32	0.37	-16
23	0.12	90	1.7	1.0	0.25	590	0.088	0.096	-9
24	0.12	90	1.7	3.0	0.25	1770	0.16	0.14	12
25	0.095	90	1.65	1.0	0.25	580	0.07	0.076	7
26	0.095	90	1.65	5.0	0.1	1200	0.16	0.18	13

5. CONCLUSIONS

The developed computer program for numerical studies of the process of machining permits the determination of the conditions and basic dynamic characteristics of the process of machining, the performance of numerical simulations of the dynamic system, and the presentation of graphic characteristics of the simulations performed.

The simulations performed permit the conclusion that:

- a change of rotary speed causes a change in the time of stabilisation of the transient run,
- a change of the thickness of machined layer causes a corresponding change of response to unit step of feed, at constant time intervals,

- a change of feed rate causes a change in the values of machining force at steady state,
- changes in the phase characteristics are the most observable during changes of rotary speed, while in the case of changes of feed rate and thickness of machined layer the differences are small,
- changes in the amplitude characteristics can be observed mainly in the case of changes in the thickness of machined layer.

The value of relative divergences between the experimental data and data from the simulations, δ (%), equal to 9.61%, indicates a good fit of the model to the actual run of the process of turning. The results obtained can be used a starting point for further research in the field of design of automatic adjustment systems.

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Abaqus, composite structures, numerical analysis, critical forces, buckling

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NUMERICAL ANALYSIS OF BUCKLING AND CRITICAL FORCES IN A CLOSED SECTION COMPOSITE PROFILE

Abstract

This paper reports the results of a numerical analysis of buckling in a carbon-fibre reinforced plastic (CFRP). The analysis involved determination of the first buckling mode and critical forces for the tested composite. The composite was tested for six different ply orientations. The analysis was performed on a closed section composite column. The objective of the analysis was to determine critical forces affecting the composite profiles with the applied ply orientations and, thus, to determine the laminate ply orientations which can carry the heaviest loads. The numerical modelling and all computations were performed using the Abaqus 6.14 software. In the analysis, we took account of boundary conditions and performed a discretization process in order to obtain correct results.

1. INTRODUCTION

The problem of modern engineering materials is important for mechanics, strength testing and machine design. Carbon-epoxy structures having higher strength properties compared to traditional materials are more and more widely used in many branches of industry.

The current trend in engineering is to use materials which are thin-walled, lightweight and have high mechanical properties at the same time. In contrast to structures made of traditional materials, the strength of modern carbon-epoxy composite materials subjected to a long-term operation decreases to a much lower extent.

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CFRP profiles are much lightweight than steel or aluminium and have much higher strength properties. As a result of many years of research into composite materials, it was possible to clearly define their material properties via the properties of matrix and reinforcement which make up composite laminates. Epoxy resin profiles are widely used in the aircraft industry. Due to technological progress, it is now required to implement lightweight structures which have a higher strength than those used at the beginning of development and production of aircraft subassemblies.

The load-carrying capacity of composite structures described in this paper is determined by a phenomenon which is commonly referred to as "loss of stability".

There are numerous works devoted to the investigation of composite profiles with different sections depending on their application in industry. A vast majority of the works on the problem of composite structures examine profiles with different types of open cross sections and geometric shapes.

The authors of the works [3, 4, 10, 11] introduced the fundamentals of design in the Abaqus system. Dealing with typically static problems, they demonstrated how to use the programme properly in order to describe a computational process correctly.

The publications [1, 2, 5, 7–9] report the results of investigations into composite structures. Their authors investigated the problems directly connected with buckling of thin-walled composite profiles having both open and closed sections. In addition to this, they also analyzed post-buckling states. They determined critical loads that given profiles can carry at the moment of stability loss. The results reported in these publications enabled the author of this paper to conduct further numerical analyses.

There is a growing interest in the problem of thin-walled composite structures due to mechanical properties of these materials. The design of composite structures is time-consuming and requires vast knowledge about properties of these structures in order to define and solve investigated problems correctly.

Problems connected with instability of composite profiles are one of the trends in both research studies and industrial development. Numerical environments such as Abaqus enable us to solve problems for suitably defined material properties and boundary conditions in real processes, and, as a result, we can perform a pre-production analysis of thin-walled composite structures.

If a numerical problem of profile buckling is defined correctly, the behaviour of real thin-walled structures will be modelled correctly, too.

2. MATERIALS AND METHODS

The study involved designing a numerical model of a profile made of carbon-fibre reinforced plastic (CFRP). The numerical model was designed using the Abaqus software. The material was ascribed linear-elastic properties in two-dimensional state of stress and had six independent material properties.

The test specimen was modelled as an orthotropic laminate, so its mechanical properties were typical of this kind of composite material, i.e. Young's modulus in fibre direction was equal to $E_1 = 130.71$ GPa, while that perpendicular to fibres was $E_2 = 6.36$ GPa; Poisson's ratio was $\nu = 0.32$; Kirchhoff's modulus describing non-dilatational strain was the same for all three directions, i.e. $G_{12} = G_{13} = G_{23} = 4.18$ GPa. Finally, the total height of the tested thin-walled composite column with a square closed section (40 x 40 mm) was exactly 300 mm.

The structure of the laminate was modelled by standard shell elements consisting of 6 plies. The thickness of a single ply was 0.131 mm, so the total thickness of the composite was 0.786 mm.

The paper investigates six different configurations of composite ply orientations. Every investigated configuration of ply orientation was strictly symmetric.

The below table lists all tested ply orientations of thin-walled composite columns.

Tab. 1. Comparison of composite ply orientations
[source: own study]

Ply orientation	
K1	0/45/90/90/45/0
K2	0/90/45/45/90/0
K3	45/0/90/90/0/45
K4	45/90/0/0/90/45
K5	90/0/45/45/0/90
K6	90/45/0/0/45/90

Ply orientation has a significant effect on strength properties of every structure. Structures with suitably selected ply orientations can carry much heavier loads than structures with random ply orientations. The essence of thin-walled composite structure design is to make them capable of operation under heavy load.

The solved problem was a typically static problem which did not took account of the object's weight or time of analysis. This work strictly refers to generally considered issues related to the strength test of thin-walled structures. Described issue is a typical problem to be solved in the analysis of stability.

A figure given below shows the Abaqus-generated numerical model of the tested composite and a ply orientation denoted as K4.

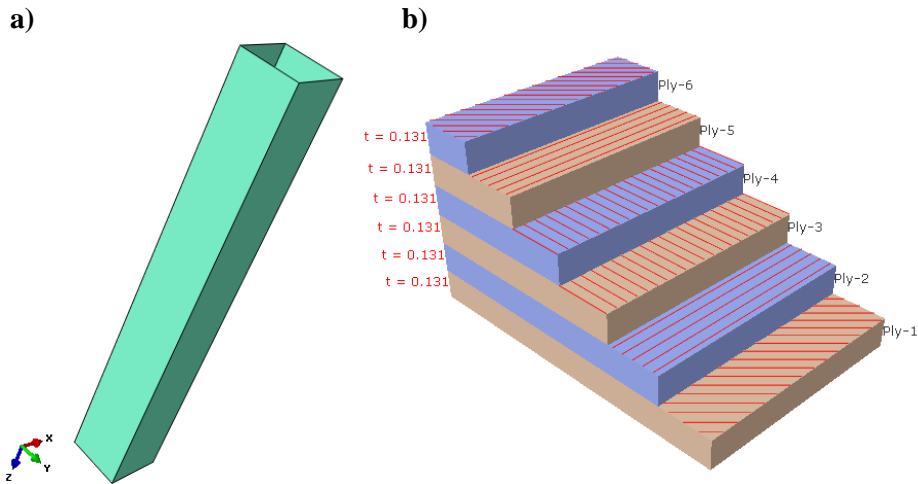


Fig. 1. Test specimen: a) numerical model, b) ply orientation K4 [source: own study]

The numerical model was analyzed only with respect to the state of instability. The objective of the analysis was to determine only the first mode of buckling and critical force for thin-walled profiles with all tested ply orientations.

The numerical model was defined by boundary conditions which enabled obtaining a correct mode of stability loss. The upper and lower edges of the profile were described by the relationships which made it possible to continue the analysis. The lower edges of the profile were fully blocked and prevented from displacement, hence $U_1 = U_2 = U_3 = 0$. The translational degrees of freedom in the profile's upper edges were blocked only in the direction of axes X and Y, hence $U_1 = U_2 = 0$; however, the thin-walled structure could move towards axis Z.

The unit force applied to the profile's edges acted on each of the four edges in a uniform manner, thereby simulating compression of a thin-walled composite structure. The unit force describing the upper edges of the structure was the ratio of the unit load to the sum of lengths of all four upper edges of the profile – hence, the load was equal to 1 (as a unit force) / 160 (i.e. the sum of edge lengths).

Buckling is generated by the compressive unit force acting on the thin-walled profile. The instability of the numerical model led to generating a specific number and shape of corrugations (half waves) within the entire composite structure.

The boundary conditions describing the numerical model and the direction of load from the unit force are shown in a figure given below.

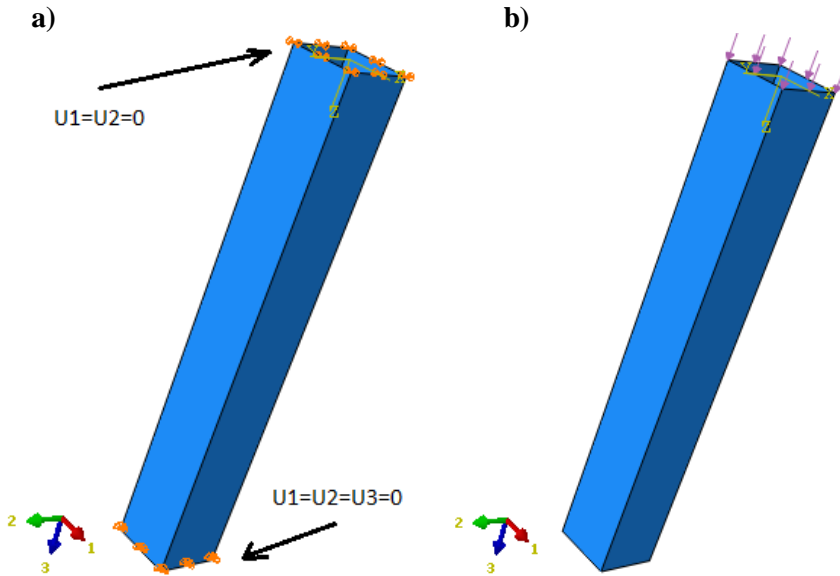


Fig. 2. Boundary conditions of the numerical model [source: own study]

The discretization of the numerical model was performed based on correctly defined mesh of finite elements. The shape of a thin-walled profile was a basic geometric solid, that is – a square stretched to an adequate length to create a composite column. The mesh was made of S4R elements, i.e. four-node, doubly curved elements with reduced integration.

The model consisted of 5200 finite elements and 5252 nodes. The mesh of the numerical model is shown below.

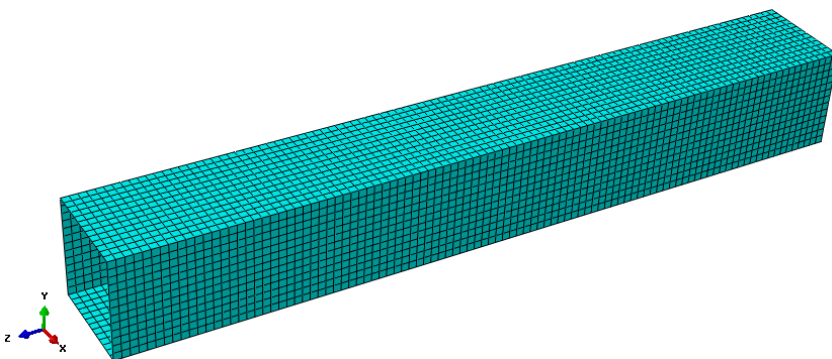


Fig. 3. FEM mesh of the numerical model [source: own study]

3. RESULTS

The numerical analysis involved determination of the first mode of buckling in composite columns for every tested ply orientation. In addition to this, critical forces were calculated for every ply orientation based on the pre-defined unit force.

The figures given below illustrate the first buckling mode for each of the analyzed ply orientation and the magnitudes of the critical force which causes buckling of the profile.

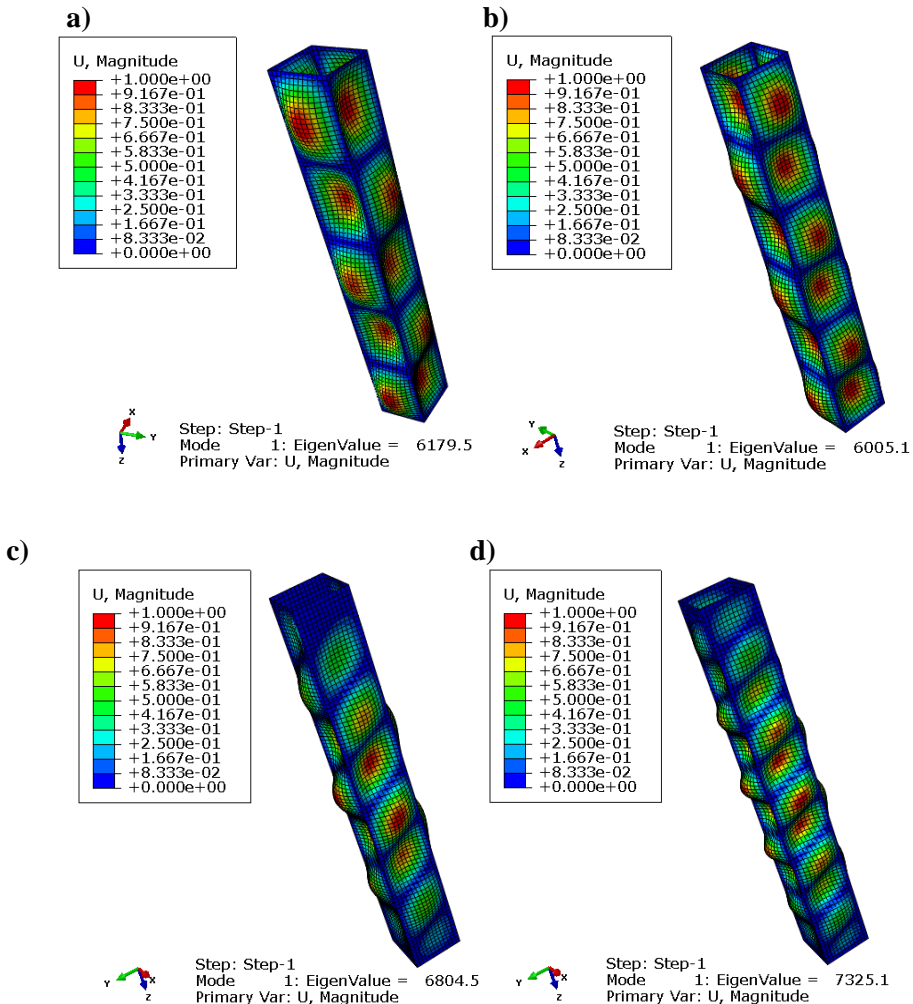


Fig. 4. Modes of instability and critical forces (eigen value) for the following ply orientations:
a) K1-0/45/90/90/45/0, b) K2-0/90/45/45/90/0, c) K3-45/0/90/90/45/0, d) K4-45/90/0/0/90/45
[source: own study]

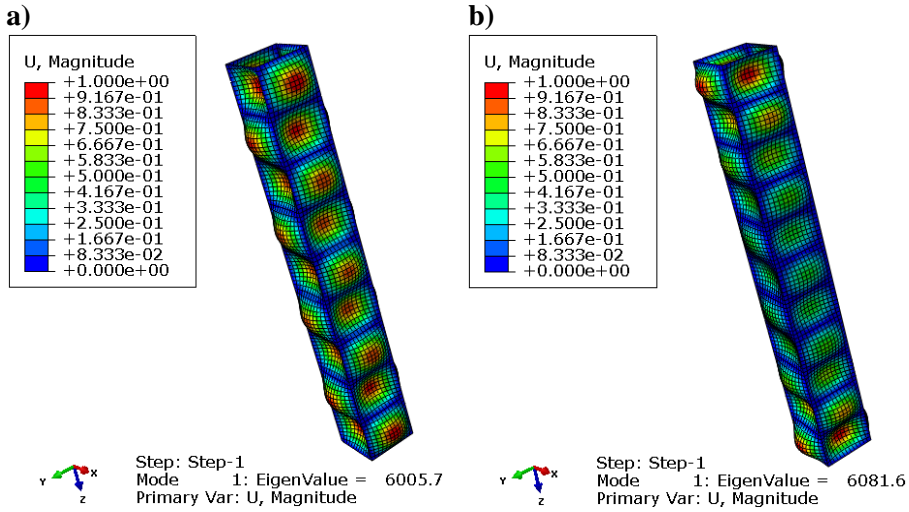


Fig. 5. Modes of instability and critical forces (eigen value) for the following ply orientations: a) K5-90/0/45/45/0/90, b) K6-90/45/0/0/45/90 [source: own study]

Based on the results of instability and critical forces (eigen values), it is possible to establish a hierarchy of thin-walled profiles in terms of their rigidity, from higher rigidity profiles to profiles having lower rigidity. The profiles with the ply orientations 0/90/45/45/90/0 (K2) and 90/0/45/45/0/90 (K5) had almost the same critical force. In the first case, this force is equal to 6005.1 N, while in the other – it is 6005.7 N, which proves that they were put under a very similar load.

The differences in operation of the analyzed profiles mainly consisted in a different number of generated half-waves. Other profiles reveal a significant discrepancy both in terms of critical forces and the number of half-waves produced in the compression process. Profiles described by the ply orientations 45/0/90/90/0/45 (K3) and 45/90/0/0/90/45 (K4) were characterized by the highest rigidity, as both of them could carry the highest loads. A thin-walled column with the ply orientation 45/90/0/0/90/45 (K4) was characterized by a critical force of 7325.1 N; this load was by 22% higher than that of the profile described as K2.

Profiles with lower critical forces such as K1, K2, K5, K6 are more energy-consuming than others. The higher rigidity and energy absorption of thin-walled composite structures results from their adequate laminate ply orientation. The analysis enabled thorough investigation of the behaviour of closed section composite profiles.

4. CONCLUSIONS

Numerical modelling is an ideal tool for simulating real processes and – provided a problem is defined correctly - can generate desired results.

The analysis of six different laminate ply orientations in a column made of carbon-fibre reinforced plastic (CFRP), give only initial information about the character of post-critical deformations. In addition, the next step in this study should be a non-linear analysis using FEM method. The results of numerical analysis should be confronted with the results obtained on the way of experimental analysis, in order to verify the results obtained by finite element method. The next steps of the research will be associated with the carrying out of experimental analysis.

In the aircraft and automotive industries, it is important to use light yet rigid and high-strength subassemblies which should often be capable of absorbing generated energy.

Laminate ply orientation has a vital effect on a composite structure, as a suitable ply orientation can ensure that the structure's load-carrying capacity will be by up to several dozen percent higher than it is the case with other basic ply orientations.

The results of investigation into the problem of instability and critical forces led to formulation of the following conclusions:

- thin-walled composite profiles with square closed section undergo buckling under specific critical forces,
- laminate ply orientation has an effect on loads that can be carried in a state of instability,
- depending on a laminate ply orientation, the composite operates under applied load at a different number of half-waves,
- the number of half-waves in a given ply orientation of a thin-walled composite structure only describes the behaviour of the composite material but has no effect on the determined critical force,
- depending on manufacturing and technological demand, it is possible to produce thin-walled composite columns which have higher rigidity or energy consumption,
- symmetric ply orientations beginning and ending with the 45° ply are characterized by a significantly higher rigidity, while the structures which begin with 90 ° and 0 ° plies have a considerably high energy absorption,
- profiles with a symmetric ply orientation are characterized by an even distribution of load over the entire length of the model, which is proven by the presence of symmetric and evenly distributed half-waves over a length of these structures.

The numerical results demonstrate initially that composite structures with square closed section, can carry diverse loads depending on a laminate ply orientation.

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Economizer, main part of boiler, modelling, CFD

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MODELING OF FLOW AND TEMPERATURE FIELD IN AN ECONOMIZER

Abstract

This article deals with the economizer as one of the main parts of a boiler. Economizers and air heaters perform a key function in providing high overall boiler thermal efficiency by recovering the low level energy from the flue gas before it is exhausted to the atmosphere. The most common and reliable economizer design is the bare-tube, in-line, cross-flow type. To reduce capital costs, most boiler manufacturers build economizers with a variety of designs to enhance the controlling gas-side heat transfer rate. From this point of view it creates a lack for an investigation and modeling of these parts.

1. INTRODUCTION

Economizers are basically tubular heat transfer surfaces used to preheat boiler feedwater before it enters the steam drum (recirculating units) or furnace surfaces (once-through units). The term economizer comes from early use of such heat exchangers to reduce operating costs or economize on fuel by recovering extra energy from the flue gas [2]. Economizers also reduce the potential of thermal

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shock and strong water temperature fluctuations as the feedwater enters the drum or waterwalls. Fig. 1 shows the location of an economizer in a coal-fired boiler. The economizer is typically the last water-cooled heat transfer surface up-stream of the air heater.

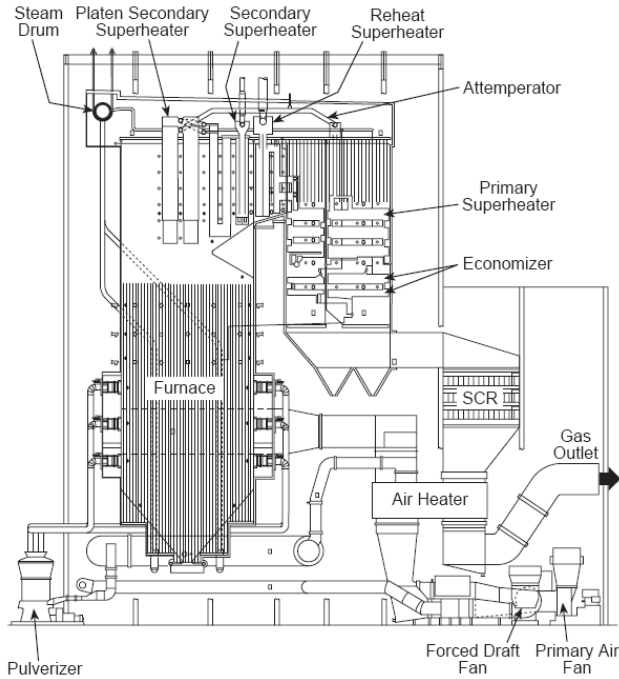


Fig. 1. Economizer and air heater locations in a typical coal fired boiler [9]

Modern heat exchangers (economizers) are characterized by high steam pressure and temperature values, and the tubes used in these devices have complex cross-sectional shapes [3, 4]. Tube geometry allows the construction of heat exchanger plates with smooth sidewalls, which can be placed in the upper part of the combustion chamber. This prevents erosion of superheater tubes and deposition of slag and ash in the spaces between adjacent tubes.

The mechanisms of heat transfer in flow conditions are complex because they may comprise the phenomena of natural forced convection and convection associated with the turbulent flow of medium in the tubes. Computational Fluid Dynamics (CFD) software and the results of laboratory tests of thermal conductivity make it possible to model the real phenomena occurring in heat exchangers. Other test methods are dedicated to specific economizer designs. The authors of [7], for example, present a mathematical model of a shell-and-tube heat exchanger with helical baffles (STHXsHB) in which the rate of heat transfer and the total cost of energy are subject to multi-objective optimization.

Modeling results can also be used to validate the adequacy of mathematical models and the accuracy of equations used in those models. Simulations conducted using FLUENT 6.3 software have been used to solve the equations of continuity, momentum, and energy in [8].

Studies [4, 6] present the results of modeling of flow and heat processes in superheaters with complex flow systems. In those works, 3D models have been replaced by 2D models. The proposed computation method can be used in subcritical and supercritical boilers.

The application of simplified models based on the finite element method (FEM) to calculate the steady-state temperature field and flow in tubes remains a basic study method that allows one to obtain results with an error not exceeding 5% [1]. The results one obtains are the basis for optimizing the geometry of economizers and selection of pumps which set the fluid in motion. In this article, FEM modeling was used to determine the stress fields and temperatures of economizer components.

2. ECONOMIZER SURFACE TYPES

Bare Tube – the most common and reliable economizer design is the bare tube, inline, cross flow type shown in Fig. 2a. When coal is fired, the fly ash creates a high fouling and erosive environment. The bare tube, in line arrangement minimizes the likelihood of erosion and trapping of ash as compared to a staggered arrangement shown in Fig. 2b. It is also the easiest geometry to be kept clean by sootblowers. However, these benefits must be evaluated against the possible larger weight, volume and cost of this arrangement.

Extended Surface – to reduce capital costs, most boiler manufacturers build economizers with a variety of fin types to enhance the controlling gas-side heat transfer rate. Fins are inexpensive parts which can reduce the overall size and cost of an economizer. However, successful application is very sensitive to the flue gas environment. Surface cleanability is a key concern. In selected boilers, such as PRB coal-fired units, extended surface economizers are not recommended because of their peculiar flyash characteristics.

Stud fins: Stud fins work reasonably well in gas-fired boilers. However, stud finned economizers can have a higher gas-side pressure drop than a comparable unit with helically-finned tubes. Studded fins perform poorly in coal-fired boilers because of high erosion, loss of heat transfer, increased pressure loss and plugging resulting from flyash deposits.

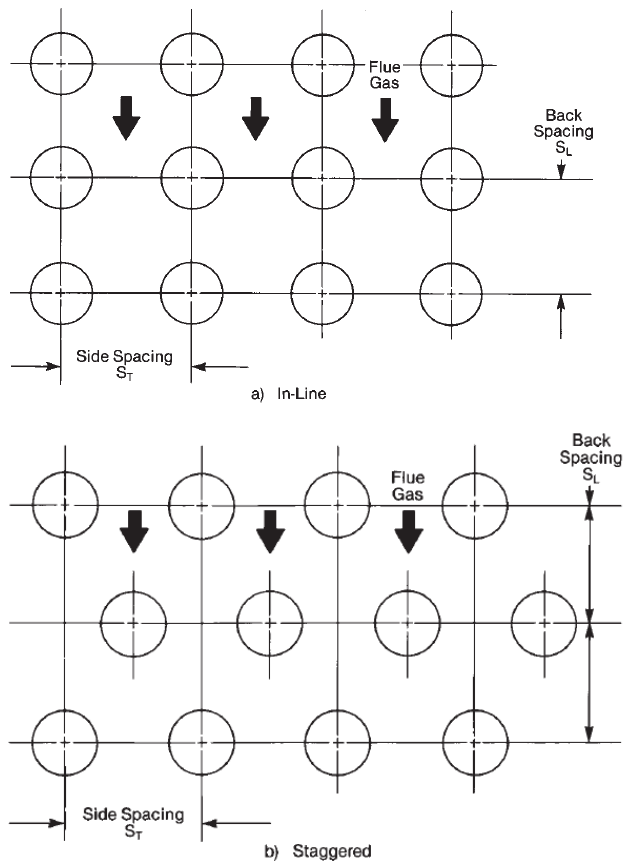


Fig. 2. Bare tube economizer arrangements [source: own study]

Longitudinal fins: Longitudinally-finned tubes in staggered crossflow arrangements (Fig. 3) also do not perform well over long operating periods. Excessive plugging and erosion in coal-fired boilers have resulted in the replacement of many of these economizers. In oil- and gas-fired boilers, cracks occur at the points where the fins terminate. These cracks propagate into the tube wall and cause tube failures in some applications. Plugging with flyash can also be a problem (tight spaces).

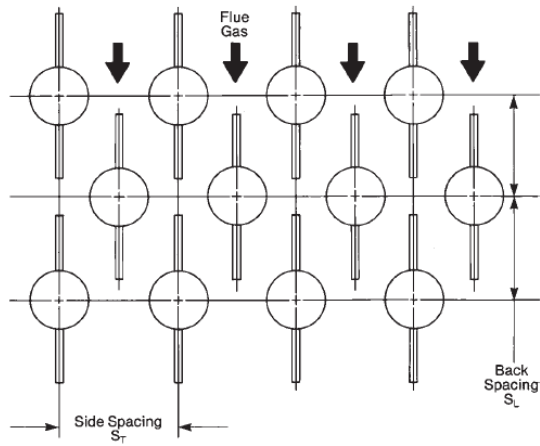


Fig. 3. Longitudinal fins, staggered tube arrangement [source: own study]

Helical fins: Helically-finned tubes (Fig. 4a) have been successfully applied in some coal-, oil- and gas-fired units. The fins can be tightly spaced in the case of gas firing due to the absence of coal flyash or oil ash. Four fins per inch (1 fin per 6.4 ram), 1.5 to 1.9 mm thick and 19.1 mm high are typical. For 51 mm outside diameter tubes, these fins provide ten times the effective area of bare tubes per unit tube length. If heavy fuel oil or coal is fired, a wider fin spacing must be used and adequate measures taken to keep the heating surface as clean as possible. Economizers in units fired with heavy fuel oil can be designed with helical fins, spaced at 13 mm intervals. Smaller fin spacings promote plugging with oil ash, while greater spacings reduce the amount of heating surface per unit length. Sootblowers are required and the maximum bank height should not exceed 1.2 to 1.5 m to assure reasonable cleanability of the heating surface. An in-line arrangement also facilitates cleaning and provides a lower gas-side resistance.

Rectangular fins: Square or rectangular fins, arranged perpendicular to the tube axis on in-line tubes as shown in Fig. 4b, have been used occasionally in retrofits. The fin spacing typically varies between 13 and 25 mm and the fins are usually 3.18 mm thick. There is a vertical slot down the middle because the two halves of the fin are welded to either side of the tube. Most designs are for gas velocities below 15.2 m/s. However, because of the narrow, deep spaces, plugging with flyash is a danger with such designs.

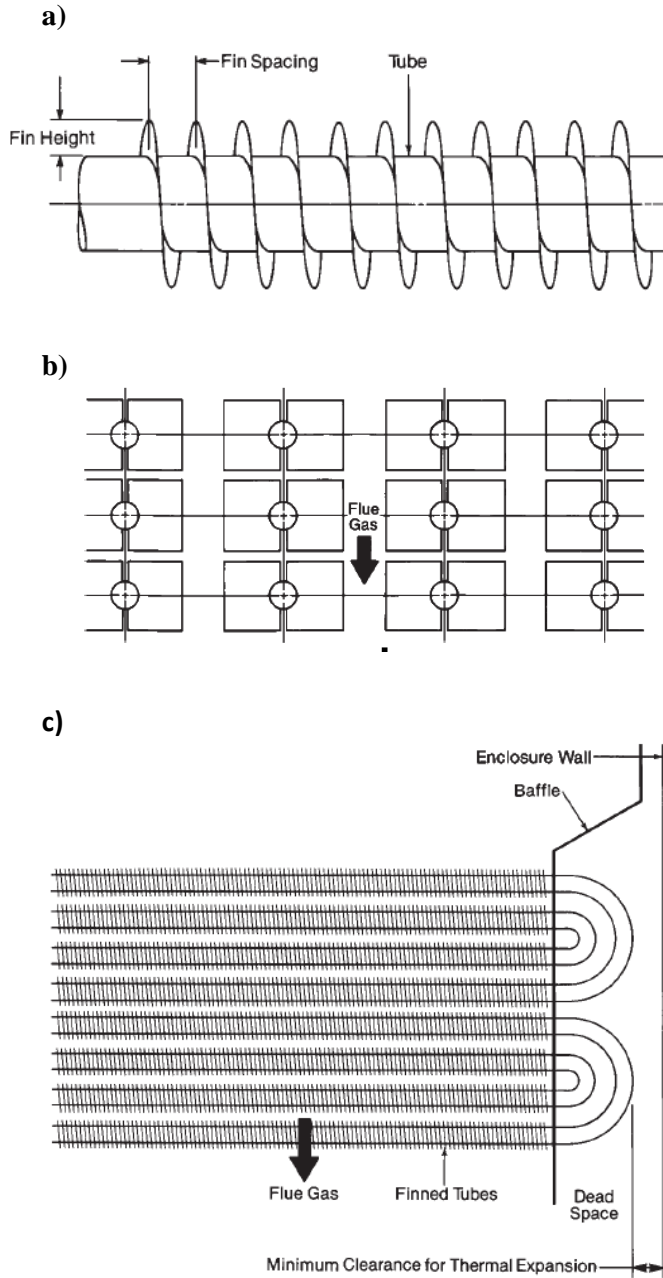


Fig. 4. Components: a – helically-finned tubes, b – rectangular fins, c – fully baffled [source: own study]

Baffles: The tube ends should be fully baffled (Fig. 4c) to minimize flue gas bypass around finned bundles. Such bypass flow can reduce heat transfer, produce excessive casing temperatures, and with coal firing can lead to tube bend erosion because of very high gas velocities. Baffling is also used with bare tube bundles but is not as important as for finned tube bundles. Tube bend erosion can be alleviated by shielding the bends.

Velocity limits the ultimate goal of economizer design is to achieve the necessary heat transfer at minimum cost. A key design criterion for economizers is the maximum allowable flue gas velocity (defined at the minimum cross-sectional free flow area in the tube bundle). Higher velocities provide better heat transfer and reduce capital cost. For clean burning fuels, such as gas and low ash oil, velocities are typically set by the maximum economical pressure loss. For high ash oil and coal, gas-side velocities are limited by the erosion potential of the flyash. This erosion potential is primarily determined by the percentage of Al_2O_3 , and SiO_2 in the ash, the total ash in the fuel and the gas maximum velocity. Experience dictates acceptable flue gas velocities. Note: PRB coal contains ash with a low erosion potential. Velocities above 21.3 m/s can typically be allowed for such coals. Further criteria may also be needed. For example, a 1.5 m/s reduction in the base velocity limit is recommended when firing coals with less than 20% volatile matter. In other cases, such as Cyclone boilers, high flue gas velocities can be used because much less flyash is carried into the convection pass, as a large part of the ash (> 50%) is collected at the bottom of the boiler as slag. The particles that enter the boiler furnace are also less erosive.

For a given tube arrangement and boiler load, the gas velocity depends on the specific volume of flue gas which drops as the flue gas is cooled in the economizer. To maintain the gas velocity, it can be economical to decrease the free flow gas-side cross-section by selecting a larger tube size in the lower bank of a multiple bank design. This affords better heat transfer and reduces the total heating surface.

3. A MODELING APPROACH TO ECONOMIZER DESIGN

As it has been mentioned above the goal of this study was to get a closer look at flow in the economizer part of the boiler, as optimized flow can enhance the efficiency of both the boiler and the entire power plant.

In the present approach flow field was described with a 3D mathematical model developed using ANSYS FLUENT software. The model represented the simplest economizer design for which two fluids were defined: water and the flue gas. To achieve a more realistic result symmetry conditions were applied.

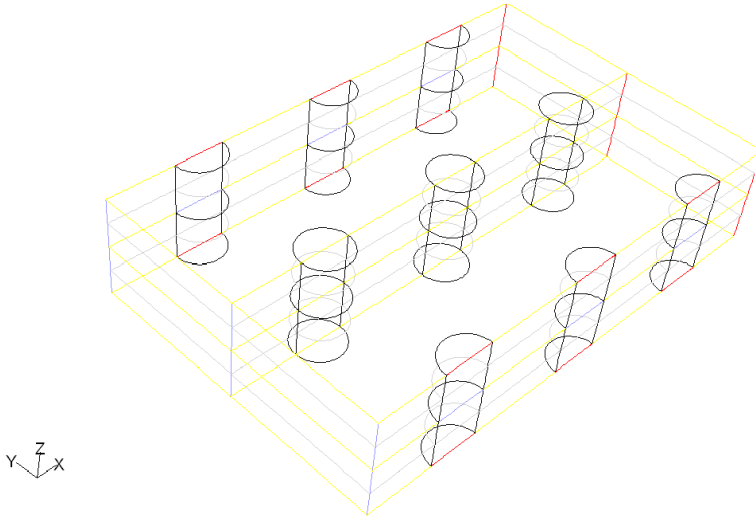


Fig. 5. A 3D model with symmetric conditions [source: own study]

In the model, water flow through pipes and the surrounding space was filled with flowing flue gas. Beside symmetry conditions, velocity inlet and pressure outlet were defined for both of these zones. Appropriate temperatures and pressure were set at velocity outlets. Convection and conduction heat transfer was considered and a suitable mesh was created for this purpose (Fig.6, 7).

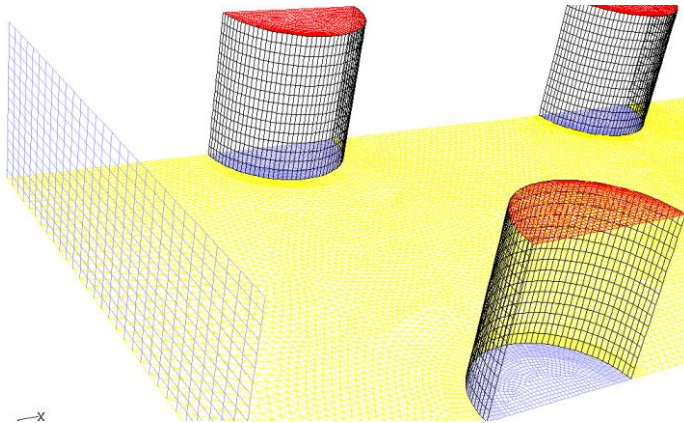


Fig. 6. Layers of elements for an appropriate heat transfer gradient around the walls [source: own study]

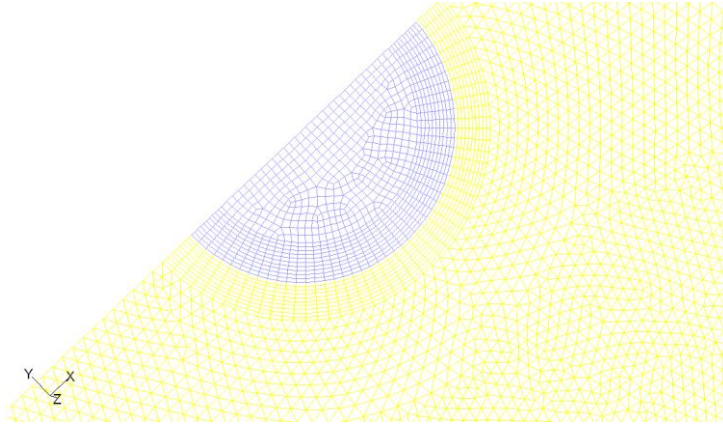


Fig. 7. Layers of elements for an appropriate heat transfer gradient [source: own study]

When the mathematical model was defined as an RNG k-epsilon model and the boundary conditions the solution could be computed. The solver was defined as steady which means that the solution was not dependent on time. Only one stationary level was examined.

By taking this approach, we were able to consider the velocity, pressure, and heat fields around the heated pipes for various types of economizer design and to use the results of the observations to choose the best design with an improved efficiency. The figures below shows the test values in a cut plane.

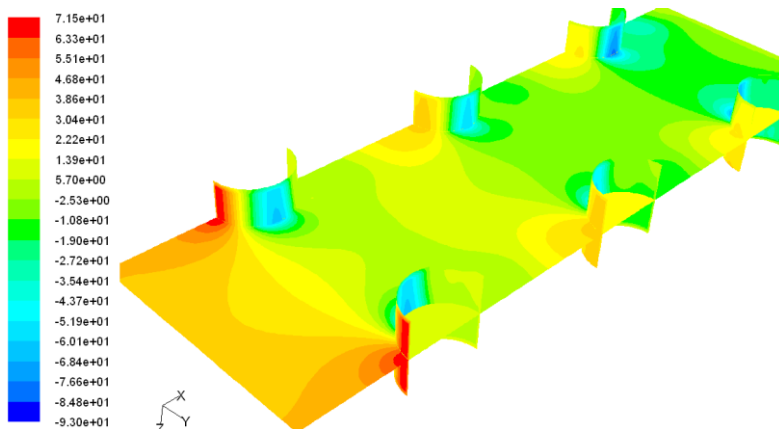


Fig. 8. Static pressure field for the simplest economizer design [source: own study]

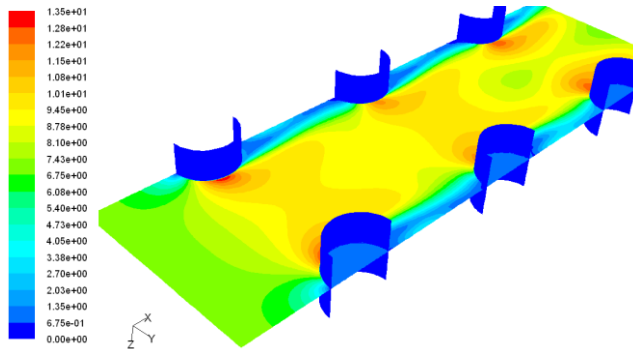


Fig. 9. Velocity flow field for the simplest economizer design [source: own study]

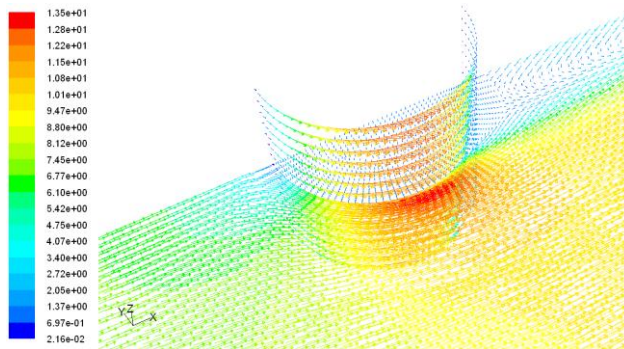


Fig. 10. Velocity vector of the flow field for the simplest economizer design [source: own study]

4. CONCLUSION

The purpose of this article was to show that CFD can be a helpful tool in optimization studies aimed at increasing the energy-transfer efficiency of a boiler or a power plant. There are numerous benefits to using a sophisticated tool such as a numerical model for engineering analysis. These modelling tools can often provide information that can only be obtained through expensive experiments or is not available from any other source. Numerical modelling can be used to obtain the required information quickly and at a reduced cost [1, 4, 5].

The primary purpose of using numerical modelling is to increase the understanding of physical processes. This is why it is often used in addition to or in conjunction with other available tools. Considering the economizer example described above, it is possible to use a network model on a large number of economizer designs to narrow down the selection to a few candidate designs. A full CFD model could then be used to analyze each of the candidate designs to gain a better understanding of their strengths and weaknesses.

Acknowledgement

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*knowledge management tool adoption,
Polish and German manufacturing companies, case study*

Justyna PATALAS-MALISZEWSKA*

STUDYING THE ADOPTION OF A KNOWLEDGE MANAGEMENT TOOL WITHIN GERMAN AND POLISH MANUFACTURING COMPANIES: AN EMPIRICAL CASE STUDY

Abstract

This article elaborates on the influence of motivational factors for workers in a manufacturing company in the context of the use of a knowledge management tool and is based on data obtained from 85 Polish and German Manufacturing Companies from the cross-border cooperation region of Lubuskie/Poland-Brandenburg/Germany. This is followed by a discussion of the results of empirical studies and of the supporting literature.

1. INTRODUCTION

Workers in companies should absorb, store, transform and share knowledge (both tacit and explicit) within a firm for an improvement of its performance. According Alavi and Leidner, knowledge management tools are based on information technology and support the processes of the creation, storage, transfer, and sharing of knowledge among employees [1]. Collections of tools which support explicit knowledge management include: the internet, intranets, databases, data warehouses, information systems (e.g. ERP, BI, CRM), Case-based Reasoning (CBR) applications, information boards and databases of experts. Among those tools which support explicit knowledge management within a company, we can list: knowledge maps, e-learning, web-blogs, social media, internal networks of practitioners (industry blogs), internal compendia

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of knowledge, video-conferencing, newsletters, corporate portals. Additionally, among the methods which support both kinds of knowledge management (tacit and explicit) it is possible to identify ones such as: study visits, daily formal direct meetings, daily informal meetings, coffee breaks, business trips, seminars, conferences and integration meetings.

Managers in manufacturing companies understand that they should implement new technology to support the knowledge management process within their company, (Pfisterer, Streim, and Hampe, 2013), but they still need to determinate the motivators for workers before they will be able to use the new technology for this activity [5, 19]. According to Luthans, motivation is a process that activates employees to achieve the goals of company [13]. So, workers should be motivated to the aim of facilitating the adoption and use of a knowledge management tool. Therefore, it is necessary to identify the motivational factors for workers in a manufacturing company that contribute to a successful adoption of new knowledge management tools.

Based on this concept, this paper elaborates the main motivational factors for workers in a manufacturing company in the context of the adoption and use of a knowledge management tool. Using survey data from 62 Polish Manufacturing Companies from the Lubuskie region; and from 23 German Manufacturing Companies from the Brandenburg region - it is possible to present a set of critical factors for the adoption (by workers) of new technologies to support the knowledge management process in a company in the cross-border cooperative region of Lubuskie/Poland-Brandenburg/Germany.

The remainder of this paper is organized as follows. Section 2 presents the theoretical background of the study. Section 3 describes the research methods. Section 4 explains the research methodology, discusses the results and provides a conclusion of the research. Section 5 summarizes the research results.

2. MOTIVATIONAL FACTORS FOR WORKERS CONTRIBUTING TO THE IMPLEMENTATION OF A KNOWLEDGE MANAGEMENT TOOL

In the literature there are generally two approaches to motivation: theories on factors of motivation and general-process theories on motivation [15]. According to the approach on the factors of motivation used in this study, the significance of motivational factors for workers contributing to the implementation of a knowledge management tool in a manufacturing company is investigated.

Among the theories of factors of motivation, Król and Ludwiczynski distinguish the following theories of motivation [10]:

- McGregor's X and Y theory,
- Herzberg's two-factor theory,
- reinforcement theory,
- expectations theory.

Vera-Munoz, Ho and Chow describe motivation as a major factor that influences an employee to share his/her knowledge [20]. Moreover, Lu et al. state that a worker's beliefs about the usefulness of IT tools is the most important determinant in the adoption of this tool in a company [12]. Knowledge management tools should be able to support the capture, storage and organisation of knowledge within a company [7]. Lee and Hong suggest that the major types of KM tools implemented in a company are: intranets, content management systems, document management systems, relational and object databases, groupware and workflow systems, data warehousing systems and data mining systems [11]. For a successful implementation of a KM tool in a company, it is necessary to create a company culture to facilitate the capture, storage and sharing of knowledge among employees by that KM tool [14]. Based on the studies of George and Chattopadhyay [9], Allen, Shore and Griffeth [2], Patalas-Maliszewska and Krebs [17], and Patalas-Maliszewska [18], the following motivators for workers, in the context of the ability to absorb and use a new technology for supporting the knowledge management process in a company, are defined:

- A Good Work Atmosphere (MF₁):
Company culture is defined as the most significant factor in knowledge sharing practices [4]. McDermott stated that company culture can facilitate knowledge sharing among employees [14].
- Organizational Commitment (MF₂):
In this study, organizational commitment describes the extent to which an employee wants to be a part of an organization [3].
- Internal Communication (MF₃):
The internal communication concept relates to whether or not senior managers and all employees communicate with each other [21].
- Training (MF₄):
It is argued that training may improve the work attitudes of employees [6].
- Coaching (MF₅):
According to Evers et al., it has been observed that providing coaching enhances outcome expectancies and self-efficacy [8].
- Internally Organized Meetings (MF₆):
It is argued that meetings can serve to maintain solidarity and collegiality between the chair and any participants [16].

According to the results of the literature study, it is possible to define the following research model (Fig. 1):

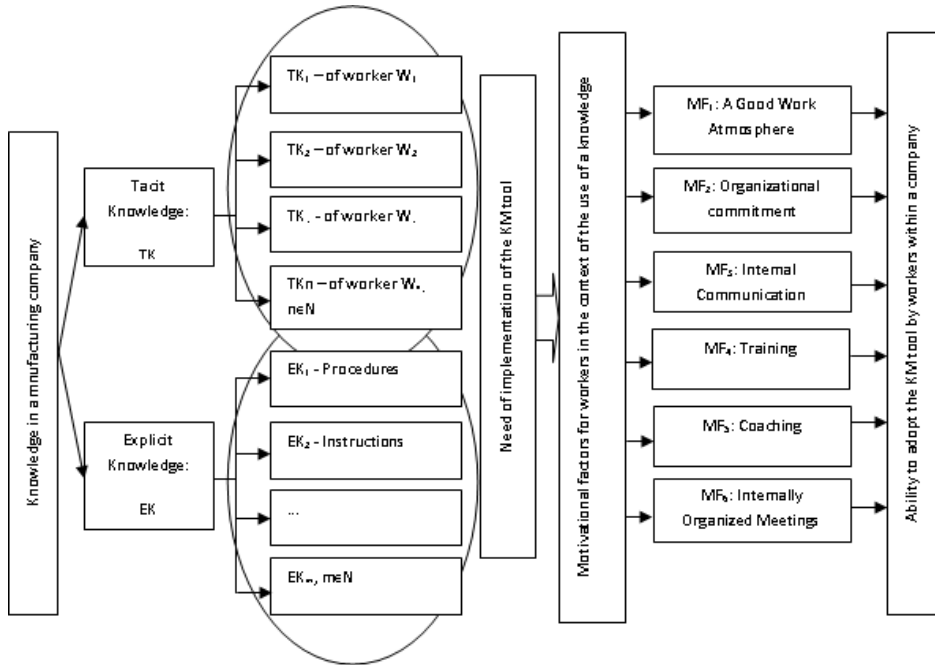


Fig. 1. A concept model [source: own study]

The conceptual model posits, from the preceding argument, that workers in a manufacturing company will be able to absorb and use a KM tool if they are motivated appropriately. So, the question arises of which motivational factors for workers contributing to the implementation of a knowledge management tool enable their ability to adopt this KM tool within a company?

3. RESEARCH METHOD

In order to describe the ability to adopt a KM tool within a company, survey data were collected from 62 Polish Manufacturing Enterprises from the Lubuskie region and from 23 German Manufacturing Enterprises from the Brandenburg region between January to September, 2014 (Polish Enterprises), and between November 2015 to January 2016 (German Enterprises). Additionally, data were collected from 85 manufacturing enterprises from cross-border cooperative region of Lubuskie/Poland and Brandenburg/Germany in which the companies were categorised as either “construction” or “automotive”, or “others”. The distribution of the categories of companies was strictly defined numerically:

- Polish manufacturing companies (N = 62): construction: 24 (39%), automotive: 30 (48%), others: 8 (13%),
- German manufacturing enterprises (N = 23): construction: 5 (22%), automotive: 15 (65%), others: 3 (13%).

The manufacturing companies in the research were approached and surveyed in the form of direct meetings, email surveys and/or phone surveys. The respondents consisted of managers (over 80%) and chief executive officers. The surveys were intentionally provided in manufacturing companies from the Lubuskie/Poland and Brandenburg/Germany cooperative region, because these regions form a special joint “cross-border area” and the chosen 85 manufacturing companies from the “automotive” and “construction” sectors contribute about 20% of those enterprises in the cooperative region.

The list of factors for the ability to adopt a KM tool in a company was based on feedback surveys and its sources are listed here:

Adopting KM tools: the degree to which there is a perceived need to support the capture, storage and sharing of tacit and explicit knowledge by information technology within a company.

- AKMT-factor1: I know that, in my organization, the use of KM tools to support the capture, storage and sharing of tacit and explicit knowledge is not very important.
- AKMT -factor2: I know that, in my organization, the use of KM tools to support the capture, storage and sharing of tacit and explicit knowledge is not important.
- AKMT -factor3: I know that, in my organization, the use of KM tools to support the capture, storage and sharing of tacit and explicit knowledge is marginally important.
- AKMT -factor4: I know that, in my organization, the use of KM tools to support the capture, storage and sharing of tacit and explicit knowledge is important.
- AKMT -factor5: I know that, in my organization, the use of KM tools to support the capture, storage and sharing of tacit and explicit knowledge is very important.

Factors that motivate workers to adopt and use KM tools in a Polish and in a German manufacturing company were based on feedback surveys and their sources are listed here:

The factors that motivate workers to adopt and use a KM tool: The degree to which the implementation of this factor within a company has a positive influence on the adoption and use of a KM tool by an employee:

- MF-factor1: I know that the implementation of motivational factors in my organization is not very important for the adoption and use of a KM tool.
- MF-factor2: I know that the implementation of motivational factors in my organization is not important for the adoption and use of a KM tool.
- MF-factor3: I know that the implementation of motivational factors in my organization is marginally important for the adoption and use of a KM tool.
- MF-factor4: I know that the implementation of motivational factors in my organization is important for the adoption and use of a KM tool.
- MF-factor5: I know that the implementation of motivational factors in my organization is not very important for the adoption and use of a KM tool.

The surveys used for testing the research model (see Fig. 1) were developed by a five-point defining scale.

4. RESEARCH ANALYSIS

The concept model was analysed using a correlation approach in order to estimate the ability to adopt and use a KM tool by workers in Polish and in German manufacturing companies. A moderated correlation approach, using Statistica ver. 10.0, was used to test the defined hypothesis. The data were carefully examined with respect to linearity, equality of variance and normality. No significant deviations were detected. Table 1 presents descriptive correlations for the main variables. Table 1 presents descriptive correlations for the main variables.

In table 1, we find descriptive correlations between the motivational factors which influence the ability to adopt and use a KM tool by workers in Polish and in German manufacturing companies. The defined interaction of the implementation of the motivational factor namely: coaching makes a contribution to the ability to adopt and use a KM tool by employees (corr = 0.3274) in Polish Manufacturing Enterprises, and also in German Manufacturing Enterprises this relationship makes a major contribution (corr = 0.5006). The other relationship between the motivational factors and the ability by workers to adopt and use a KM tool are not expressed either in Polish or in German companies. It is very interesting that similar research results were received from both German and Polish Manufacturing Enterprises (based on research results from Polish and German Companies in a special joint cross-border region of Lubuskie/Poland and Brandenburg/Germany). This may possibly be a good recommendation for an area of further cooperation between Polish and German manufacturing companies in this special region regarding the field of knowledge transfer among workers in those companies.

Tab. 1. Research results [source: own study]

Construct/Item: AKMT–factor1/ AKMT–factor2/AKMT–factor3/ AKMT–factor4/ AKMT–factor5–MF–factor1/ MF–factor2/ MF–factor3/ MF–factor4/ MF–factor5	Correlation	r2	t	p
Polish Manufacturing Companies				
MF ₁ / AKMT	0.0933	0.0087	0.7261	0.4706
German Manufacturing Companies				
MF ₁ / AKMT	-0.0575	0.0033	-0.2638	0.7945
Polish Manufacturing Companies				
MF ₂ / AKMT	0.0663	0.0044	0.5149	0.6085
German Manufacturing Companies				
MF ₂ / AKMT	0.2184	0.0477	1.0254	0.3168
Polish Manufacturing Companies				
MF ₃ / AKMT	0.2381	0.0567	1.8993	0.0623
German Manufacturing Companies				
MF ₃ / AKMT	0.1791	0.0321	0.8343	0.4136
Polish Manufacturing Companies				
MF ₄ / AKMT	0.0714	0.0051	0.5545	0.5813
German Manufacturing Companies				
MF ₄ / AKMT	0.1910	0.0365	0.8915	0.3827
Polish Manufacturing Companies				
MF ₅ / AKMT	0.3274	0.1072	2.6841	0.0094
German Manufacturing Companies				
MF ₅ / AKMT	0.5006	0.2506	2.6499	0.0150
Polish Manufacturing Companies				
MF ₆ / AKMT	0.0526	0.0028	0.4076	0.6850
German Manufacturing Companies				
MF ₆ / AKMT	0.3437	0.1182	1.6771	0.1083

To determine the nature of significant interactions of the factor: *coaching*, which influence the ability of employees to adopt and use a KM tool in manufacturing companies, the study tests the research model using regression analyses which estimate this effect. The success of the implementation of a KM tool in a manufacturing company clearly increases when knowledge workers are motivated by coaching. Therefore, a potential AKMT model, which describes the potential chance of success for the adoption of a KM tool, for the manufacturing companies surveyed in this study can be formulated (see Fig. 2):

$$AKMT = 2.5227 + 0.2846 \times MF_5 \quad (1)$$

where: *AKMT* – the significance of the ability of employees in a manufacturing company to adopt and use a KM tool,

MF₅ – the motivational factors for employees in a manufacturing company for the ability to adopt and use a KM tool.

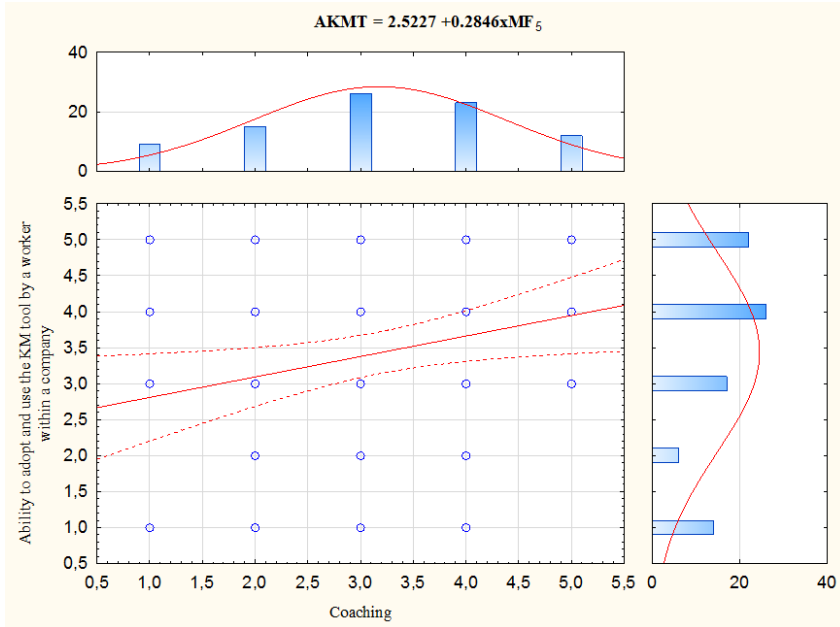


Fig. 2. An AKMT model [source: own study]

This study was motivated by the actual needs of the managers of Polish and German manufacturing companies in the joint cross-border area: Lubuskie/Poland and Brandenburg/Germany, who have a need to implement a knowledge management tool to support the capture, storage and sharing of tacit and explicit knowledge within a company. Hence starting with a review of the different motivational factors for employees used in the companies under study, the author identified that the motivational factor: *coaching* may well be very helpful in adopting a new technology to act as a KM tool in a manufacturing company. A theoretical model was developed and tested; however, it confirmed that the use of the motivational factor: *coaching* plays a strong relevance regarding the ability to adopt and use a KM tool by workers within a company.

5. CONCLUSIONS

This research analysis highlights the need for the implementation of coaching, as indicated by the success of the factor: *coaching*, for workers in the context of improving the ability to adopt and use a new technology for supporting knowledge management processes in a company. The study was based on empirical results from 85 manufacturing companies in the joint cross-border area: Lubuskie/Poland and Brandenburg/Germany.

The empirical findings of this study confirm the positive influence of the one motivational factors: *coaching* on the ability of workers to adopt and use a KM tool. Also it is suggested that managers in a manufacturing company, when they decide to implement a new KM tool, should incorporate a motivator for workers: coaching, in this way improving the likelihood of success of the implementation process. When firm are investing in specialized information technology, firms need to invest in additional resources to safeguard the success of KM-tool implementation.

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knee joint, endoprosthesis, finite elements analysis

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COMPUTER AIDED DESIGN AND STRUCTURAL ANALYSIS OF THE ENDOPROSTHESIS OF THE KNEE JOINT

Abstract

The paper presents results of the preliminary structural analysis of model of the endoprosthesis of the knee joint. Basics of anatomy and biomechanics of the knee joint were introduced. Based on data from computed tomography, the model of knee joint was constructed. The prototype of the endoprosthesis of the knee joint was designed. After determining physical properties of structural materials, the Finite Elements Analysis of the model was conducted under various load conditions. Finally the results of analysis are presented.

1. INTRODUCTION

The aging population will increase the demand for medical services. From orthopaedics' point of view one of the most frequently performed procedures is knee replacement, or in other words an implantation of specially designed and manufactured endoprosthesis of knee joint to replace structures damaged or destroyed as a result of medical conditions or accidents. The growing demand for this type of treatment leads to the continuous expansion of the queues. The solution to this problem could be the use of modern technology and rapid prototyping in the design process of implants tailored to the individual patient. This could potentially allow to reduce the manufacturing cost of prostheses, shorten the time of surgery and hospitalization and in consequence, allow to carry out more operations.

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2. ELEMENTS OF ANATOMY AND BIOMECHANICS OF HUMAN KNEE

Mechanical function of each joint in the human skeletal system is to enable movement of the bones in the conditions of carrying loads. The knee joint is the largest joint in human body characterized by a complex structure. This joint is a combination of three bones: the femur, tibia and fibula. The joint includes a patella. The knee is the joint that transmits the loads that occur when moving between these elements. Schematic structure of the knee joint is presented in Fig. 1. It consists of femoral-tibial joint, patellofemoral joint and ligament complex [1, 2].

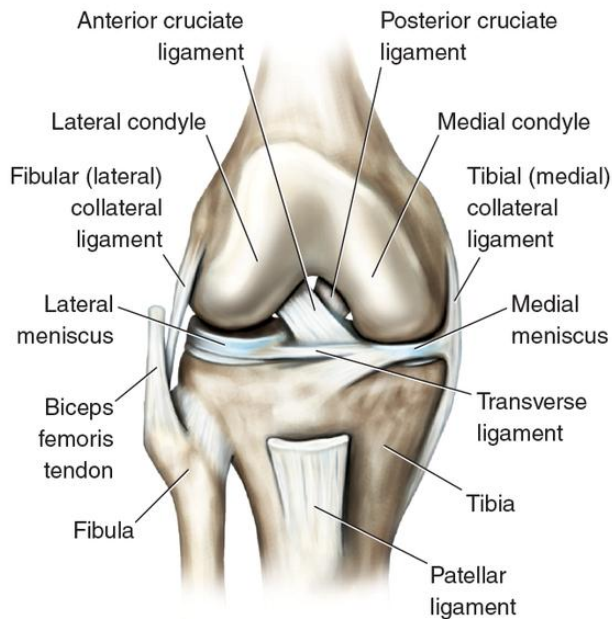


Fig. 1. Human knee in extension [18]

The main element of the knee is the femoral-tibial joint. Acetabulum is formed by two condyles of the tibia (medial and lateral), and further deepened by the meniscus (medial and lateral) [2, 3]. The menisci have very good elastic properties. Their function is mainly shock absorption occurring during the movement and distribution of the pressure over a larger area. The condyles of the femur create the joint heads. Articular cartilage that covers the condyles of the femur and tibia, is to provide lossless sliding motion, and protect the knee against overloads. All the joint surfaces are covered with hyaline cartilage [1, 3].

The movement of bending and straightening the knee joint is held in the sagittal plane. The configuration of the articular surfaces and the range of motion depends on the number of degrees of freedom, as well as loads that occur in the joint. Anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) combine closely the femur and tibia. During the rotation of the bent knee ligaments they wrap around each other. The rotation of the knee joint is possible only when the knee is flexed, this movement is blocked at both the full knee extension and at maximum flexion. The maximum internal rotation is 40° while the external rotation is about 52° . Knee in flexion shown in Figure 2. The maximum possible to obtain range of movement in the knee joint can vary between healthy individuals [2, 3, 4, 5].

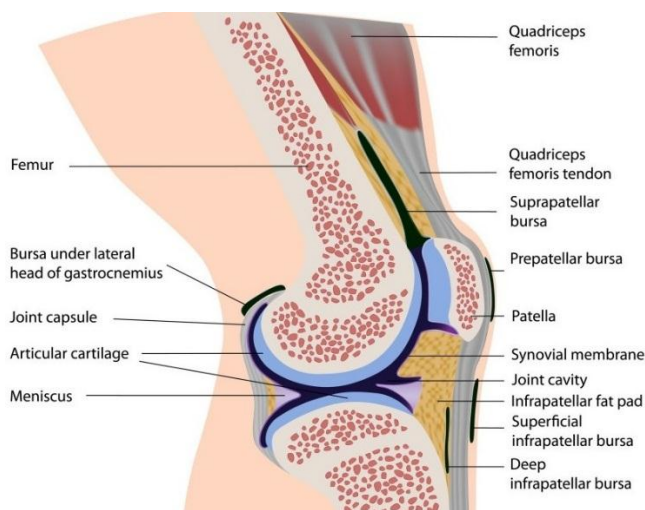


Fig. 2. Human knee in flexion [19]

During full extension the stabilisation of the knee joint is provided primarily by the geometry of the distal femur and the proximal end of the tibia. Stabilisation of the joint in the transverse direction is provided by medial and lateral collateral ligaments.

The knee joint is surrounded by a strong joint capsule, isolating it from the environment and ensuring stabilization. With the provided therein to synovial fluid responsible for the damping and lubricating the entire connection. Synovial bursa is responsible for the production of synovial fluid. The structure of articular cartilage, and synovial fluid properties make the coefficient of friction of the joint at a typical load is 0.0026, and the maximum load value is 0.0038. For comparison, the coefficient of friction two-oiled metal surface is from 0.3 to 0.5 [3, 6].

In the proper functioning of the knee joint an important role plays heterotopic bone – patella. The patella is connected with a joint with a patellar tendon and quadriceps tendon. This bone has a role in stabilising the anterior aspect of the knee joint, and protecting it from the excessive overload. Patella moves during flexion and extension along the surface of the articular patellofemoral joint on the femur. During this movement, only about 25% of the articular surface of the patella is adjacent to the femur [3, 7].

Shape of the articular surface and the structure of ligaments fundamentally define the scope of the characteristics of motion of the joint. The connection between the femur and the tibia is a kinematic pair of Class IV. There is a possibility for the rotational movements in relation to two axis (flexion and rotation), however the rotational movement is blocked in third axis (abduction and adduction) and the translational movement (mainly anteroposterior). The knee joint is mainly adapted to transmit the vertical compressive load [1, 3].

The knee joint is transferred highest stress in comparison to other joints of the human body. The values of these loads are dependent on activity. The internal forces of muscles and external forces have an effect on the knee. An example of an external force may be the force of gravity. Also the important factors include: the weight of the human body, the force occurs in the muscle, and the various angles between the axes of the parts of the body [1, 7].

The dominant scheme of the knee loads is Maqueta model. While standing on both legs knees are loaded about 85% by whole body weight. This is due to the fact that the load does not include the legs below the knees. On the other hand, in the case of standing on one leg joint will be load about 93% of body weight.

Andriacchi said, that he axial load carried by the knee joint during stair climbing or the level walking can be 1,3, while during the run can be twice the weight [8]. According to O. Schipplein, loading of the joint may be five times the value of the weight of a human during a run. In turn, the results of experiment as presented by S. Scott D. Winter show that the knee can be loaded with a force exceeding eleven times the body weight. These are extreme cases and leading to injury, although it illustrates the amount of load that the knee must withstand [9].

3. PROJECT OF THE ENDOPROSTHESIS OF THE KNEE JOINT

To complete the project the advanced engineering software – CAD was used, which led to the creation of three-dimensional elements of the bones of the knee joint on the basis of images obtained from CT and the individual elements of the prosthesis. It also uses software CAE to calculate the strength of the endoprosthesis. The following programs were used during production: Materialise Mimics, Solid Edge and Solidworks.

The first step in creating models of the bone is to generate the mask by selecting the tissue using the Hounsfield scale, within the lower 120 and upper 3.071. Then, the mask created would be trimmed using the Crop tool Mask to cover the bones comprising the knee joint. This process is carried out in several stages in order to generate the most accurate model of the bones. This step consisted of generating a three-dimensional model resulting from the trimmed mask, with the help of tool – Generate 3D model. The models obtained in this manner require considerable refinement by supplementing the missing parts of the surface. The final effect of this process is presented in Fig. 3.

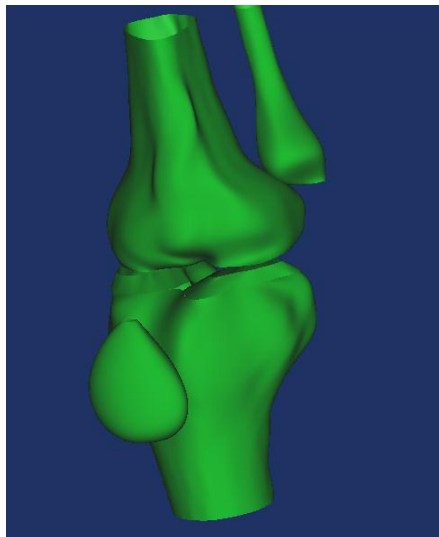


Fig. 3. Surface models of all the bones of the knee [source: own study]

Created three-dimensional model was then exported to the .igs file. This file format allows to open it in a program such as Solidworks and to perform the stress analysis.

Prepared in this way models were used to design the knee endoprosthesis used for knee replacement. It is important that all the dimensions of the bones and the distance between them have been preserved. This has a major impact on the process of designing the prosthesis closely matched to the patient. Motion of the prosthesis is based on literature data contained in U.S. Patent [10, 11, 12, 13, 14]. The model was created in SolidWorks.

As a final product the model consisting of four elements was created: base metal placed on the tibia, femoral component attached to the femur, the polyethylene liner attached to a metal base and in contact with the femoral component and a part on the kneecap, which is also made of polyethylene to protect it.

After designing the individual elements knee endoprosthesis and the preparation of models of bones respectively, full product was created and is presented in Fig. 4.

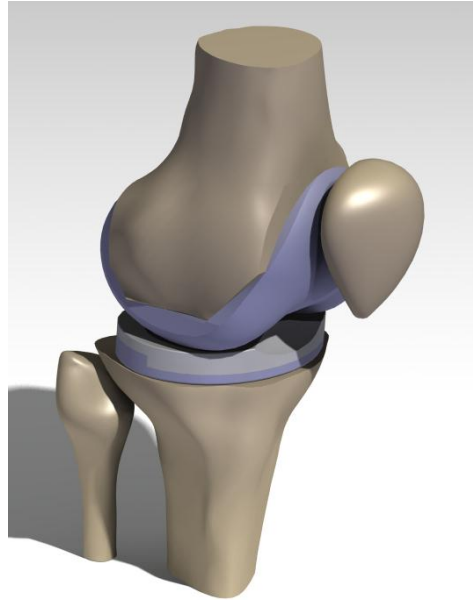


Fig.4. Assembly including bones of the knee joint merged with the endoprosthesis [source: own study]

The final stage of the design was to make the material strength of numerical simulations designed implant components. Below are presented the analysis of the strength of components of prosthesis used in study. In this paper, the polyethylene component uses high density polyethylene UHMWPE 1000 produced by "Zatorski" [7]. Table 1 presents selected physico-chemical properties of the material.

Tab. 1. Physico-chemical properties of the UHMWPE 1000 [7]

Properties	Unit	Value
Density	g/cm ³	0.93
Stress at break	MPa	>18
Elongation at break	%	17
Flexural strength	MPa	>700
Impact strength	kJ/m ²	Does not crack
SHORE hardness	–	63
Friction coefficient	μ	0.19
Grindability	μ/km	0.45

Biomaterial selected for strength calculations of base metal placed on the tibia and femoral component was cobalt alloy Co/28Cr/6Mo. Table 2 presents mechanical properties of this material.

Tab. 2. Mechanical properties of the Co/28Cr/6Mo [7]

Properties	Unit	Value
Young's modulus	GPa	235–247
Poisson's ratio	–	0.293–0.308
Elastic limit	MPa	760–839
Tensile strength	MPa	1290–1420
Compressive strength	MPa	760–839
Flexural strength	MPa	683–916
Elongation	%	25–29
Vickers hardness	HV	363–402
Rockwell hardness	–	37.1–41
Fatigue strength (10 ⁷ cycles)	MPa	342–378
Density	kg/m ³	8190–8360

4. STUDY ON STRESS DISTRIBUTION IN THE ENDOPROSTHESIS

The designed model was used to perform a series of preliminary studies including the stress distribution in the knee endoprosthesis with the use of Finite Element Analysis method. The performed studies are foundation for defining parameters for further exploitation of the prosthesis.

4.1. Software used in the study

Materialise Mimics is software specifically developed for medical image processing. It is used for the segmentation of 3D medical images, resulting in highly accurate 3D models of patient's anatomy. These patient-specific models can be implemented in a variety of engineering applications directly in Materialise Mimics or Materialise 3-matic, or exported to 3D models and anatomical landmark points to 3rd party software, like statistical, CAD, or FEA packages [15].

Solid Edge is a 3D CAD, parametric feature and synchronous technology solid modelling software. It runs on Microsoft Windows and provides solid modelling, assembly modelling and 2D orthographic view functionality for mechanical designers. Through third party applications it has links to many other Product Lifecycle Management technologies [16, 17].

Implementation of two highly-efficient graphic modellers – Parasolid and D-Cubed that allows combining direct modelling with precise control of geometry and gives engineers opportunity to conduct the designing process with speed and simplicity on a level, that has never been seen before.

Studies were performed in the environment of Abaqus software. Abaqus is the advanced CAE engineering tool. Its use is mainly the analysis of systems, using the finite elements method (FEM). In the industry, this program is used to resolve issues related to the mechanics of solids and fluids, on the strength of machines and structures, taking into account many factors such as load, temperature, electrical conductivity, etc. [7]. In this work, the Abaqus was used to analyze strength designed knee prosthesis.

4.2. Methodology of studies

After preparing the data for the program are generated Abaqus finite element mesh polygons. The last step is to create a model preparation Mesh on each part. The last step is to create a model preparation Mesh on each part.

Analyses were performed for a person weighing 70 kg. To the analysis were assumed force $F=3000N$. After these operations have been carried out numerical calculations of deformations and displacements of investigated objects. The study included the analysis properly implanted prosthesis and the case in which there is contact in only one condyle and a acetabulum (lift-off). The second case this may, in fact, however, observed it is extremely rare.

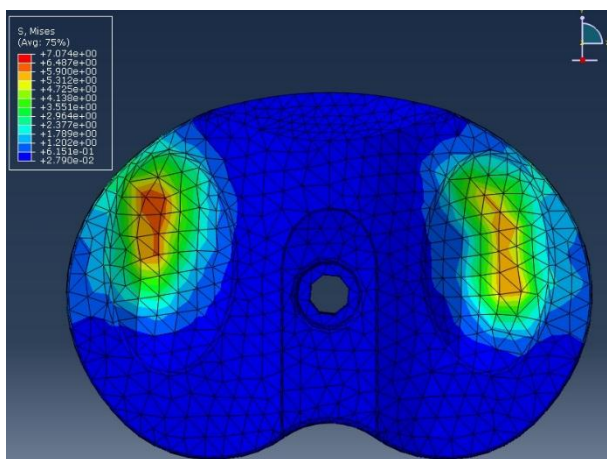


Fig. 5. Reduced stress of polyethylene pad [source: own study]

Maximum equivalent stresses occurring on the polyethylene insert amount 7MPa. While the value of contact stresses is 15MPa. Reduced stress of polyethylene pad is presented in Fig. 5.

Value of contact stresses on femoral component is 14 MPa. Equivalent stresses have not changed. Reduced stress of femoral component are presented in Fig. 6.

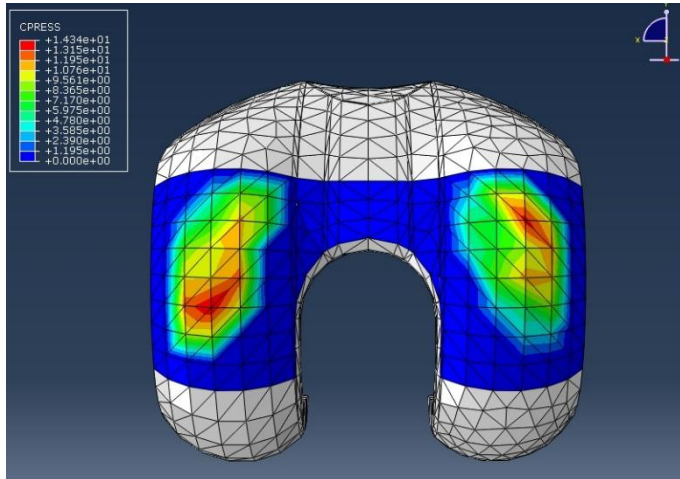


Fig. 6. Pressures established on the femur of the model [source: own study]

Reduced stress and pressure does not exceed the limit values. Therefore, this model was tested for contact in only one condyle and one of the acetabulum (lift-off). Arrangement of the elements themselves in this case is shown in Fig. 7.

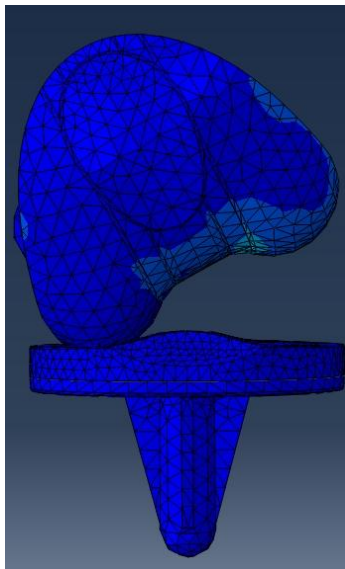


Fig. 7. The case where only one condyle in contact with the acetabulum (lift-off) [source: own study]

Reduced maximum stress occurring in a metal pad are 45MPa. Pressures up to 75 MPa while. Reduced stress of femoral component are presented in Fig.8. In the case of the femoral pressures are 27 MPa. Reduced stress of femoral component is presented in Fig. 9. Equivalent stresses occurring on a polyethylene pad amount in this case up to 16,7 MPa. Their value is doubled compared to the model, which contacts both the knuckles. While pressures are 29 MPa.

In the case that the prosthesis are in contact only one condyle and the acetabulum, the model will be probably damaged. The reduction of the contact surface causes a significant increase of the stresses and pressures. Our case lift-off was to check whether the model created can cope with such a load with limited contact. In fact, this case exists, but the forces on the prosthesis are much smaller.

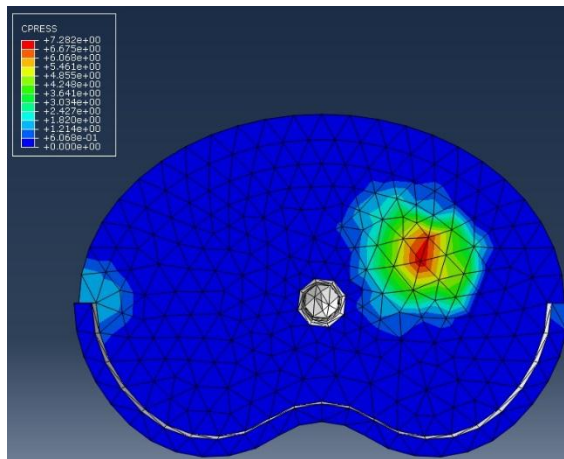


Fig. 8. The pressures occurring for lift-off on a pad metal [source: own study]

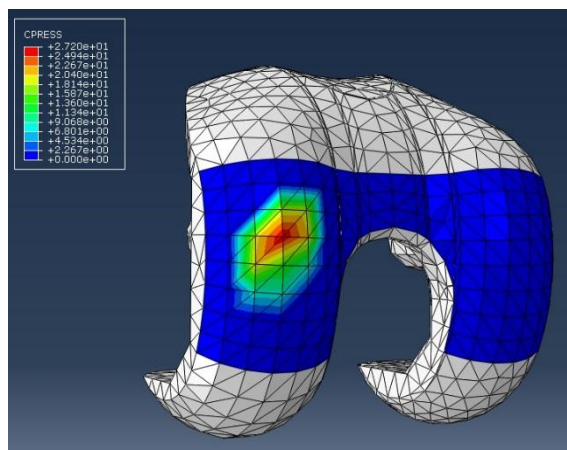


Fig. 9. Distribution of pressure on the femoral component for the case lift-off [source: own study]

5. CONCLUSIONS

Modern medicine allows the exchange of the damaged structures of the human body element artificially produced. Such procedures is due the amazing progress of science, technology and medicine.

Creating a prosthesis model for this study consisted of four main stages. The first step was to create a three-dimensional solid models of bones of the knee joint based on images from CT. For this we used Materialise MIMICS software to create surface models of the bones. Then, these models were finished and set up a full assembling of the knee using SolidWorks and Solid Edge software.

Static analysis of properly implanted prosthesis has shown that reduced stress and the pressure does not exceed the limit values. The weakest element of the model was a polyethylene liner. This is of course related to the biomaterial used in its preparation.

Analysis where only one condyle in contact with the acetabulum indicated that the reduced stress and pressure exceeds the limit values. This may be caused the fact that used considerable force, which rarely occur in properly functioning joint. In such a case it may have been damaged bone, and not part of the prosthesis.

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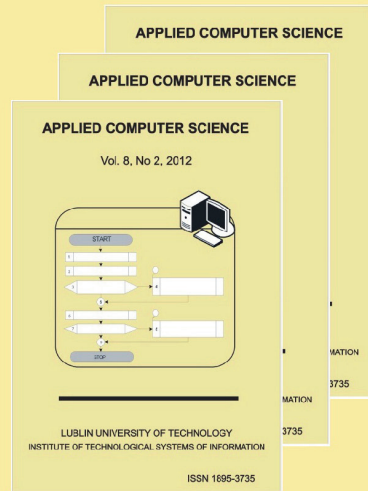
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