TRANSPORT PROBLEMS 2017 Volume 12 Issue 4
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2017.12.4.14

**Keywords:** indicator of crane safety; CAD/CAE; mobile crane; stability of a crane; overturning torque; lifting capacity; tip-over axis

**Wojciech KACALAK, Zbigniew BUDNIAK*, Maciej MAJEWSKI**
Faculty of Mechanical Engineering, Koszalin University of Technology
Raclawicka 15-17, 75-620 Koszalin, Poland
**Corresponding author*. E-mail: zbigniew.budniak@tu.koszalin.pl

# CRANE STABILITY ASSESSMENT METHOD IN THE OPERATING CYCLE

**Summary.** The article presents stability assessment of the mobile crane handling system based on the developed method with the use of the mathematical model built and the model built in the integrated CAD/CAE environment. The model proposed consists of the main crane assemblies coupled together: the truck with outrigger system and the base, the slewing column, the inner and outer arms, the six-member telescopic boom, the hook with lifting sling and the transported load. Analyses were conducted of the displacements of the mass centre of the crane system, reactions of the outrigger system, stabilizing and overturning torques that act on the crane as well as the safety indicator values for the given movement trajectories of the crane working elements.

## 1. INTRODUCTION

This study adds to the research on the mobile crane [1-3], including selected configurations of working elements' positioning together with applying load onto its outrigger system, which is the consequence of its components' and cargo's mass.

Modelling of and research on the loaded mobile crane frame's stability is a complex topic. Understanding crane's working conditions is crucial to designing an appropriate stability model which would include the mutual positions of crane's components.

The study [4-6] presented a model whose scope included the full specification of motion during cargo handling in combination with operational movements. A generalized formulation of the widely used crane model is analyzed using the method of multiple scales [7]. A comprehensive nonlinear modelling, featuring a full three-dimensional crane model and the adaptive vibration control architecture, is devised [8]. The studies [3-9] considered the influence of the outrigger system on the stability and the reaction of the ground on which the mobile crane is situated. The monograph [9] includes the challenges of modelling of and research on the dynamics of mobile cranes. The papers on crane modelling [10,11] presented the structure of crane's assemblies as well as research on the dynamics of the crane's frame.

Carrying large loads with the aid of truck mobile cranes may in certain conditions lead to a stability loss [2, 11-19]. The value of the moment required to maintain balance in relation to the tip-over axis [13, 17, 20, 21] may constitute the measure of the risk of the crane tipping over. Loading with the moment from the mass of the crane elements and the loads is additionally summed up with the moments that originate from inertia forces (caused by the movement of the cargo and its parts) and from the load with wind [22-25]. The overturning torque $M_w$ is counteracted by the stabilizing torque $M_u$ with an opposite direction that is dependent on the mass and the location of the mass centre of the crane elements (Fig. 1).

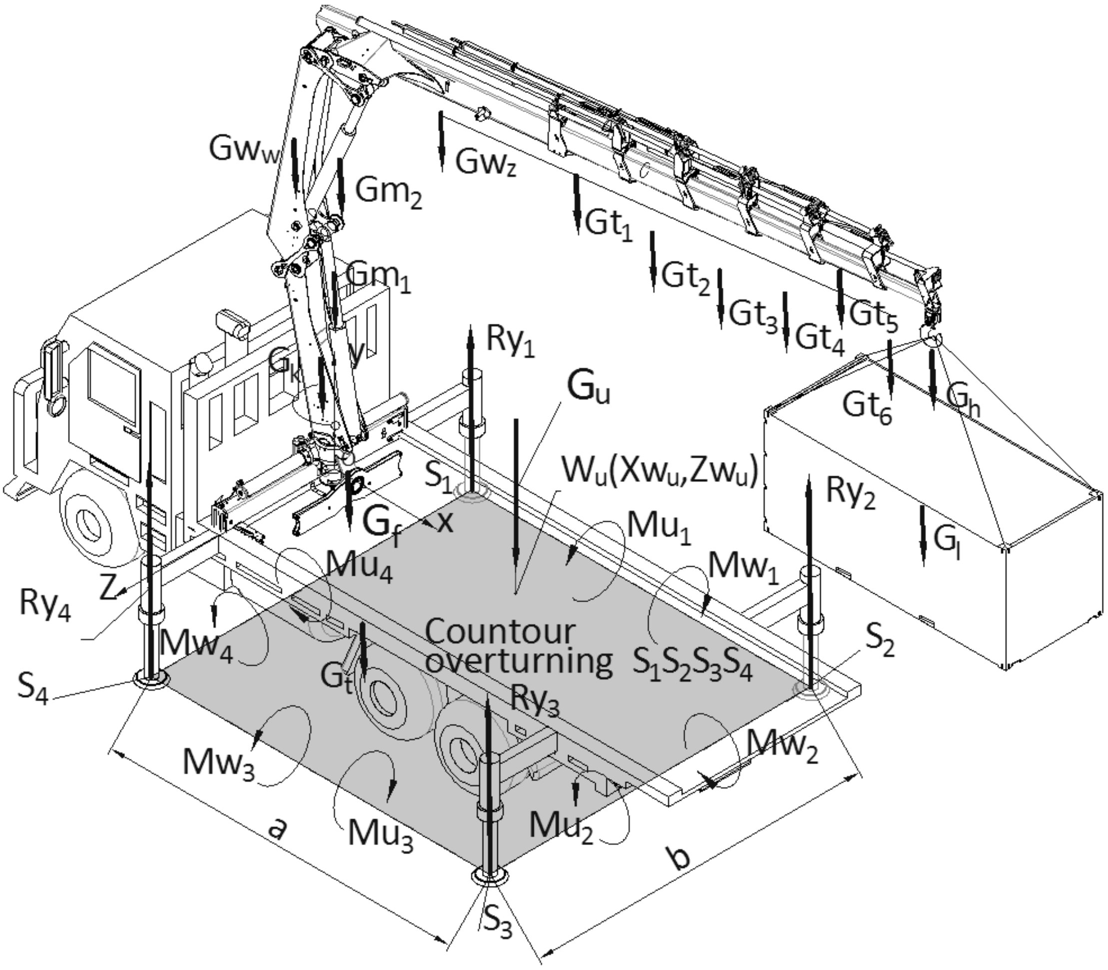


Fig. 1. Diagram of forces and torques that act on the crane outrigger system: *Gu* – total weight of the crane system; *Gf* – weight of the truck including the outrigger system; *Gb* – crane base weight; *Gk* – weight of the slewing column; $Gw_w$ – weight of the inner arm, $Gw_z$ - weight of the outer arm; $Gm_1$, $Gm_2$ – weights of hydraulic cylinders; $Gt_1$, $Gt_2$,.., $Gt_6$ – weights of the arms of the six-member crane boom; *Gh* – hook weight, *Gl* – cargo weight; $Ry_1$, $Ry_2$, $Ry_3$, $Ry_4$ – vertical reactions of the base ; *a*&*b* – spacing of the crane outriggers

According to international standards [26] and [27, 28], it is accepted that the crane is stable if at any position of the boom loaded with lifting capacity with an adequate extension, the stabilizing torque *Mu* is greater than the overturning torque *Mw* by the value of $\Delta M$.

$$\Delta M = M_u - M_w > 0 \tag{1}$$

where

$$\Delta M = \min \in (\Delta M_i), \quad \Delta M_i = Mu_i - Mw_i \tag{2}$$

$$Mu_i = \sum_{j=1}^{n} G_j \cdot d_{i_j}, \qquad Mw_i = \sum_{j=n+1}^{m} G_j \cdot d_{i_j} \tag{3}$$

$$d_{1_j} = z_j - z_{S_1}, \quad d_{2_j} = x_{S2} - x_j, \quad d_{3_j} = z_{S_4} - z_j, \quad d_{4_j} = x_j - x_{S_1}, \tag{4}$$

$i$ = 1÷4 - number of the tip-over axis; $n$ – number of the elements of the crane system, whose weight vector $G_i$ in the time of cargo transport, in a projection on the horizontal plane *Oxz* is located inside the tip-over contour that is limited by axes: $k_1$, $k_2$, $k_3$ and $k_4$; $m$ – number of all the crane system elements; $di_j$ – distance of the gravity centre of the element $j$ from the tip-over axis $i$ in the projection on the horizontal plan.

The following may also constitute the measure of the crane stability:

- the value of the pressure on the base of the least loaded crane support and the value of the changes of this force in time [1, 13, 29].
- the location of the symmetric mass centre of the handling system of the crane in relation to the support points [2, 13]. The system is stable if, in the projection on the horizontal plane, the mass centre is located inside the quadrangle that is established by the support points of the crane outrigger system.
- the indicator $W_b$ accepts values from 0 to 1. The value of the indicator of $W_b = 0$ constitutes the lower limit of safe operation. The stability indicator $W_b$ was defined as follows:

$$Wb = \min \in \left\{ \frac{\min(Ry_i)_t}{G_u \cdot k_1 \cdot (1-k_2)} - \frac{k_2}{1-k_2} \right\}_t \tag{5}$$

where:

$$t = t_e - t_b \qquad t = \sum \Delta t_j \tag{6}$$

$i = 1 - 4$ - number of the outrigger; $j =$ - number of the elementary fragment of the trajectory; $\min(Ry_i)$, kN - the smallest of the vertical reactions of the base on the outrigger $i$; $Gu$, kN - total weight of the crane system; $k_1$ - index of the maximum load of the crane outrigger, $Ry_{max} = Gu \cdot k_1$, where: $k_1 \leq 0.25$ – for a crane with four outriggers; $k_2$ - index that determines the minimum load of the crane outrigger, $Ry_{min} = Gu \cdot k_2$; $t$ , s - time of the working cycle of the handling assignment; $t_b = 0$ , s - start of the crane working cycle; $t_e$ , s - end of the crane working cycle.

In order to guarantee the stability of the crane system, the value of the indicator $W_b$ should be greater than zero when $min(Ry_i) > k_1 \cdot k_2$. The value of the indicator $k_2$ is determined considering safety on the level that depends on the crane working conditions. It was accepted that the value of this index takes into account the wind speed as well as the velocities, accelerations and pulls in the crane kinematic pairs. Pulls may be the result of the cargo frozen to the ground being torn off, the cargo being broken off, sudden breaking, hitting an obstacle etc.

From the perspective of the general principles of the safe operation of the crane, it is accepted that the value of the index $k_2$ is proportional to the speed of the wind and crane elements as well as accelerations and pulls that occur in the kinematic pairs of lever devices. Provision of the value of the index $k_2$ is one of the several alternative methods to determine the safety stock of the crane operation.

The following changes were presented as the results of simulation testing: the location of the mass centre of the crane system, the reaction of the outrigger system, stabilizing and overturning torques that act on the crane and the values of the safety indicator depending on the location of the working elements of the machine.

## 2. METHODOLOGY OF THE ASSESSMENT OF THE STABILITY OF THE CRANE HANDLING SYSTEM

The methodology as presented in Fig. 2 was used in simulation testing to assess the stability of the mobile crane handling system. The simulation model built with the use of the integrated CAD/CAE system makes it possible to assess the stability of the crane system through the example of the HIAB XS 111 crane with the proposed interaction and control system [29, 30-36].

The following are the basic elements of the method implemented:

- parametric modelling of the elements and the entire crane system in the CAD system for the defined configuration,
- determination of the system stability conditions (a notation of equations that constitute a mathematical model to calculate the following: the trajectory of the mass centres of the elements of the crane system, the reaction of the base on the crane outrigger system, the stabilizing torque $M_u$ and the overturning torque $M_w$ as well as the safety indicator),

- building of a kinematic model of the crane and carrying out simulation testing in the integrated CAD/CAE system,
- an analysis of the kinematic and dynamic quantities of the crane system during handling in connection with maintaining constant balance (stability), and
- an optimization of the trajectories of the displacements of the working systems of the crane for specific assignments taking into consideration the movement safety indicator considering the limiting conditions. By knowing the value of the safety indicator during working movements, it is possible to conduct an assessment of the risk of the loss of the crane's stability and to select the optimal displacement trajectory.

Integrated CAD - SolidWorks software as well as the module for computations and engineering analyses: CAE - SolidWorks Motion was used for the purpose of the modelling and numeric tests of the crane handling system.

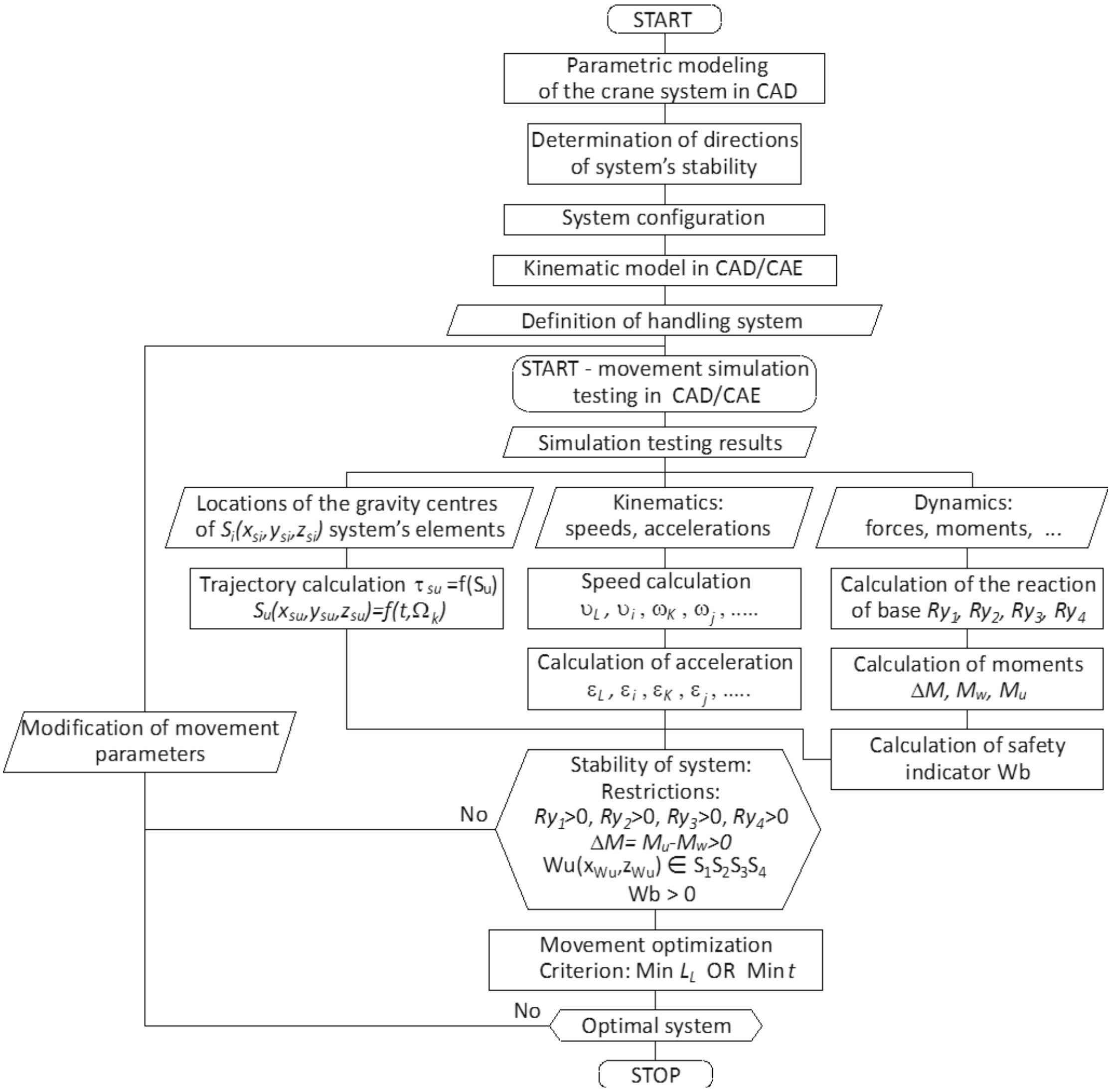

Fig. 2. Block diagram of computer aided assessment of the stability of the crane handling system

## 3. SIMULATION MODEL OF THE HANDLING SYSTEM

In simulation testing, a kinematic model was used of the mobile crane (HIAB XS 111) handling system with four degrees of freedom, which is presented in Fig. 3.

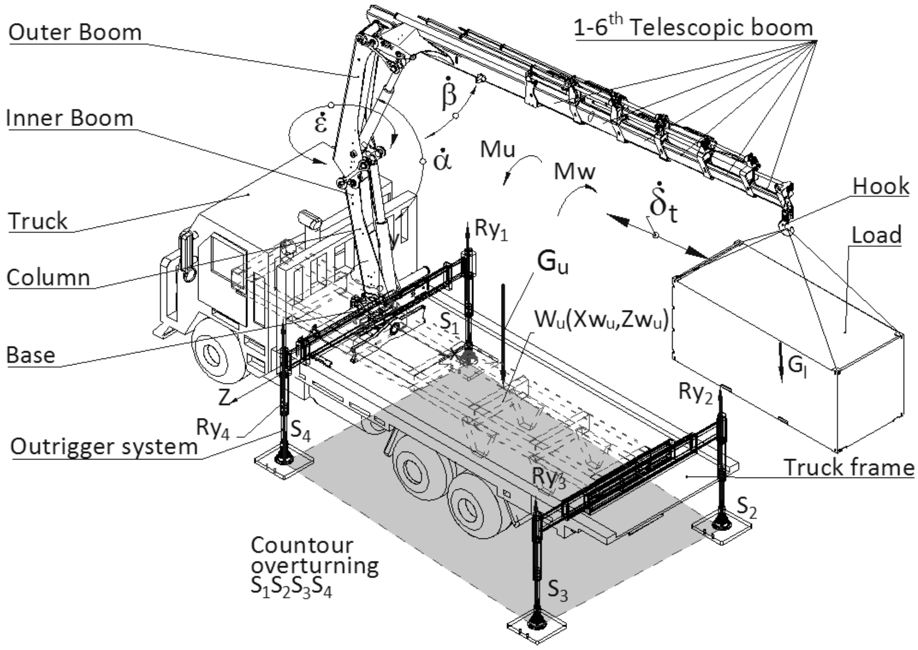


Fig. 3. The kinematic model of the handling system of mobile crane type HDS HIAB XS111

The model of the crane developed consists of the main crane assemblies coupled together: the truck with outrigger system and the base, the slewing column, the inner and outer arms, the six-member telescopic boom, the hook with lifting sling and the transported load.

Analyses were conducted of the displacements of the mass centre of the crane system, reactions of the outrigger system, stabilizing and overturning torques that act on the crane as well as the safety indicator values for the given movement trajectories of the crane working elements.

Configuration of the mobile crane's cargo handling system (Fig. 4) as a combination of connected elements was analyzed as sets of local coordinate systems (Fig. 5) connected with the crane's components. The cargo's position vector $\vec{q}_l$, in the absolute coordinate system *Oxyz*, is given with the following formula:

$$\vec{q}_l = L(x_L, y_L, z_L) = [x_L, y_L, z_L]^T = \vec{r}_f + \vec{r}_b + \vec{r}_k + \vec{r}_{Ww} + \vec{r}_{Wz} + \vec{r}_t + \vec{r}_h + \vec{r}_z + \vec{r}_l \tag{7}$$

where:

$$\vec{r}_t = \vec{r}_{t_1} + \vec{r}_{t_2} + \vec{r}_{t_3} + \vec{r}_{t_4} + \vec{r}_{t_5} + \vec{r}_{t_6} \tag{8}$$

$\vec{r}_f, \vec{r}_b, \vec{r}_k, \vec{r}_{Ww}, \vec{r}_{Wz}, \vec{r}_t, \vec{r}_h, \vec{r}_z, \vec{r}_l$ - vectors defining local coordinate systems origins' positions located at points *F*, *B*, *K*, *Ww*, *Wz*, *T*, *H*, *Z*, *L*, which belong to the truck *f*, the crane's base *b*, slewing column *k*, outer *Ww* and inner *Wz* arms, six-member telescopic boom *t*, hook *h*, lifting sling *z*, and the handled cargo *l*.

An analytical description of the configuration of the crane kinematic system involves strenuous conversions of vector-matrix equations (2-3), until explicit dependences have been obtained that determine the variable angular and linear quantities. Knowledge of these dependences is very desirable. It needs to be emphasized, however, that it is very difficult to obtain explicit dependences for the crane handling system. The integrated CAD/CAE system was therefore used to determine vectors that specify the configuration of the crane system.

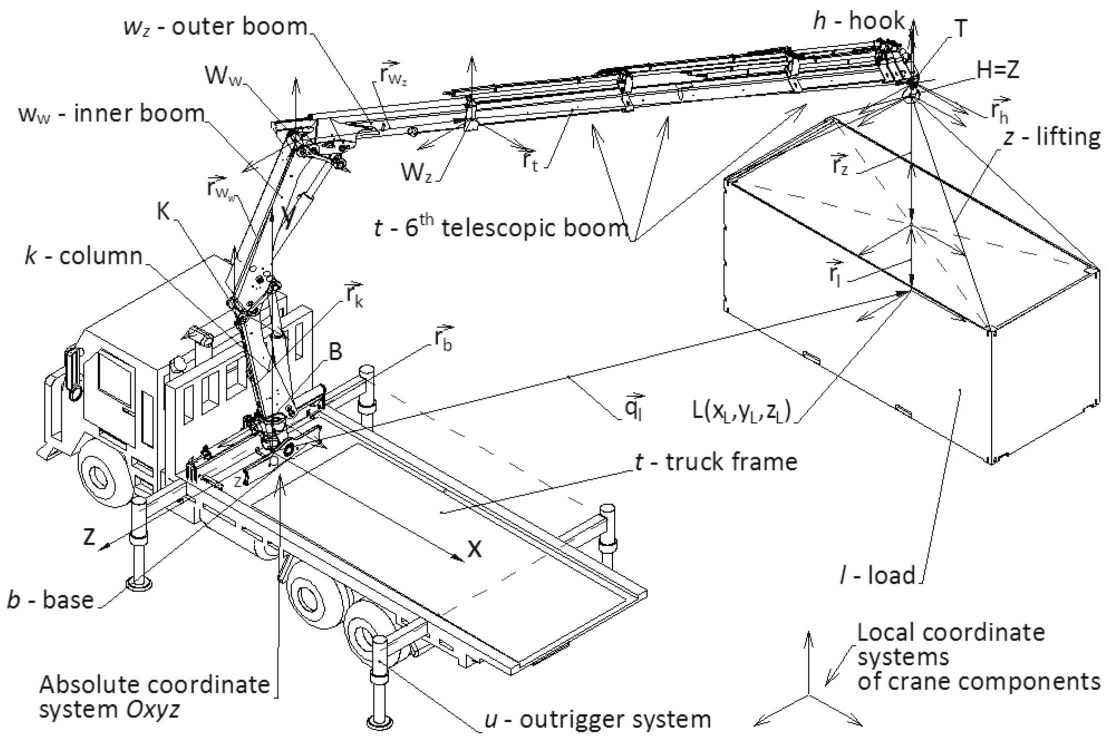


Fig. 4. Mobile crane handling system's configuration during operations

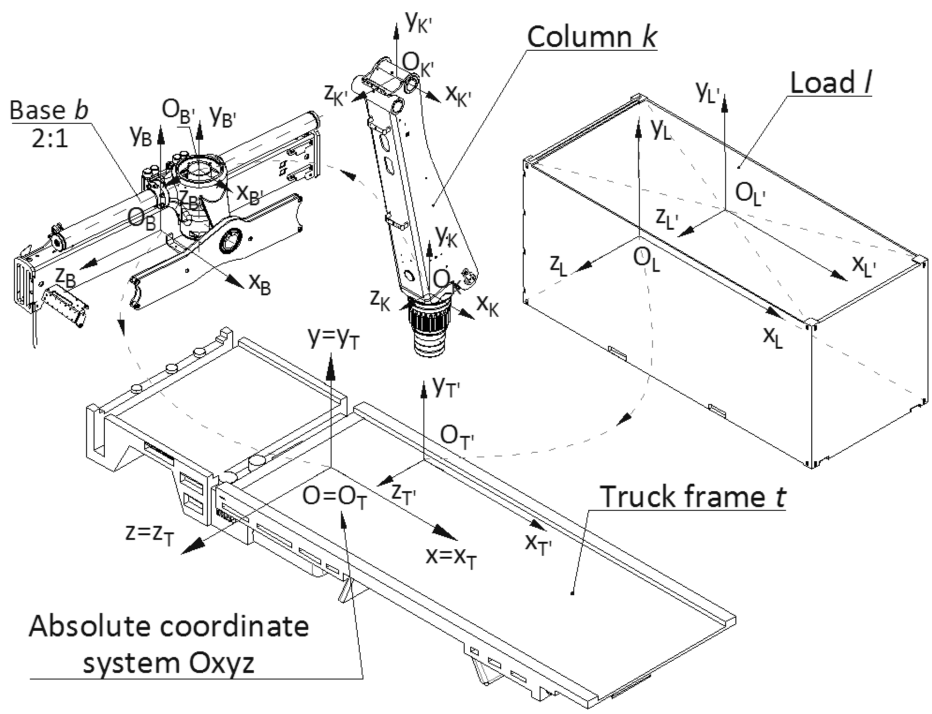


Fig. 5. Assembly overview of the vehicle's ($t$) chassis, base ($b$), column ($k$), and cargo ($l$), where local coordinate systems $O_T x_T y_T z_T$, $O_B x_B y_B z_B$, $O_K x_K y_K z_K$ and $O_L x_L y_L z_L$ are related to the main mounting base, and the local coordinate systems $O_{T'} x_{T'} y_{T'} z_{T'}$, $O_{B'} x_{B'} y_{B'} z_{B'}$, $O_{K'} x_{K'} y_{K'} z_{K'}$ and $O_{L'} x_{L'} y_{L'} z_{L'}$ are helper mounting bases

In order to determine dependences between the configuration coordinates ($\varepsilon$, $\alpha$, $\beta$, $\delta t$) and the base coordinates of the location of the cargo, temporary 3D bonds were introduced into the simulation model, which determine the location of the handling system and its elements.

In the model developed, drives were defined that perform the rotary motion of the crane column with velocity $\dot{\varepsilon}$ and linear drives that force the rotary motion of the inner and outer arms with velocities $\dot{\alpha}$ and $\dot{\beta}$ as well as sliding out of the six-member telescopic boom with velocity $\dot{\delta t}$.

## 4. RESEARCH RESULTS

The stability evaluation of the handling assignment was conducted with a mobile crane of the HDS HIAB XS111 type. The configuration of the movement of the working mechanisms of the crane during the execution of the three variants of the handling assignment is presented in Table 1, where the denotations of the location parameters were accepted according to Fig. 3. The cargo located in position A was to be transported and positioned in location B (Fig. 6).

Table 1

Parameters of sequential movements for three variants of handling assignment

| Movement sequence | Variant of cargo displacements | | |
|---|---|---|---|
| | I | II | III |
| 1 | $\Delta\beta$ = 7.2 | $\Delta\beta$ = 7.2 | $\Delta\beta$ = 7.2 |
| 2 | Δε = -189° | Δδt = -1.5 m | Δδt = 2.1 m |
| 4 | Δδt = 2.1 m | Δε = -189° | Δε = -189° |
| 4 | $\Delta\beta$ = -5.2° | Δδt = 3.6 m | $\Delta\beta$ = -5.2° |
| 5 | - | $\Delta\beta$ = -5.2° | |

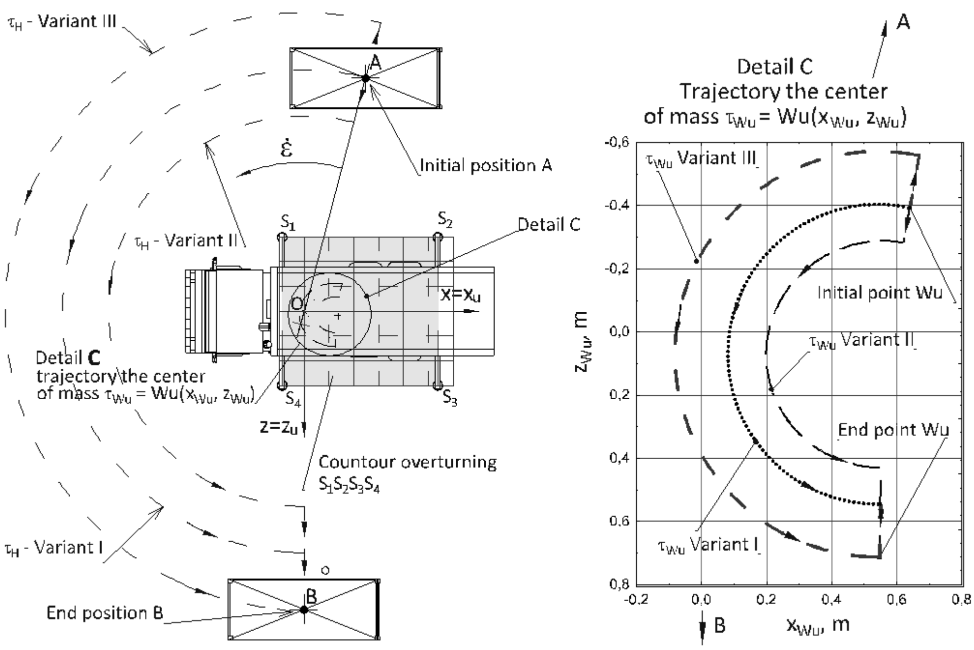


Fig. 6. Handling assignment consisting in carrying the cargo from its initial position A to position in point B, for three displacement variants

For simulation purposes, the following assumptions were accepted in simulation testing:

- in the simulation testing, the following propeller speeds were accepted: $\dot{\varepsilon}$ = 18 deg/s, $\dot{\alpha}$ = 2.5 deg/s, $\dot{\beta}$ = 5 deg/s, $\dot{\delta}$ =0,3 m/s,
- the value of the safety indicator was $k_1$ = 0.25. This means that in the most favourable position of the centre of the mass $Wu(x_{Wu},z_{Wu})$ of the crane system, in a projection on the horizontal plane, all the vertical reactions in the outriggers are identical and they constitute 25 % of the total load *Gu*,
- the value of the safety indicator $k_2$ = 0.05,
- it was accepted in the simulation testing that the crane is not subject to the wind pressure force (the wind speed is smaller than $\upsilon_w$ < 8.3 m and it is neglected),
- the working movements of the crane are smoothly controlled, hence it was accepted that inertia forces can be neglected,
- the mass of the cargo carried is $m_l$ = 560 kg.

The integrated CAD/CAE system with an additional computational application was used in simulation testing, which permitted the following among others:

- an accurate determination of the coordinates of any point of the crane system based on the mathematical model that describes its configuration [2],
- establishing the trajectory of the gravity centre of the crane $W_u$ ($x_{Wu}$, $z_{Wu}$),
- calculation of the reaction in the outriggers $Ry_1$, $Ry_2$ $Ry_3$, $Ry_4$ = f {$G_l$ , *Wu* ($x_{Wu}$, $z_{Wu}$), *t*} - [1],
- calculation of the difference of the torques $\Delta M = Mu - Mw$ = f {$G_l$ , *Wu* ($x_{Wu}$, $z_{Wu}$), *t*},
- calculation of the safety indicator *Wb* = f {$G_l$ , *Wu* ($x_{Wu}$, $z_{Wu}$), *t*}.

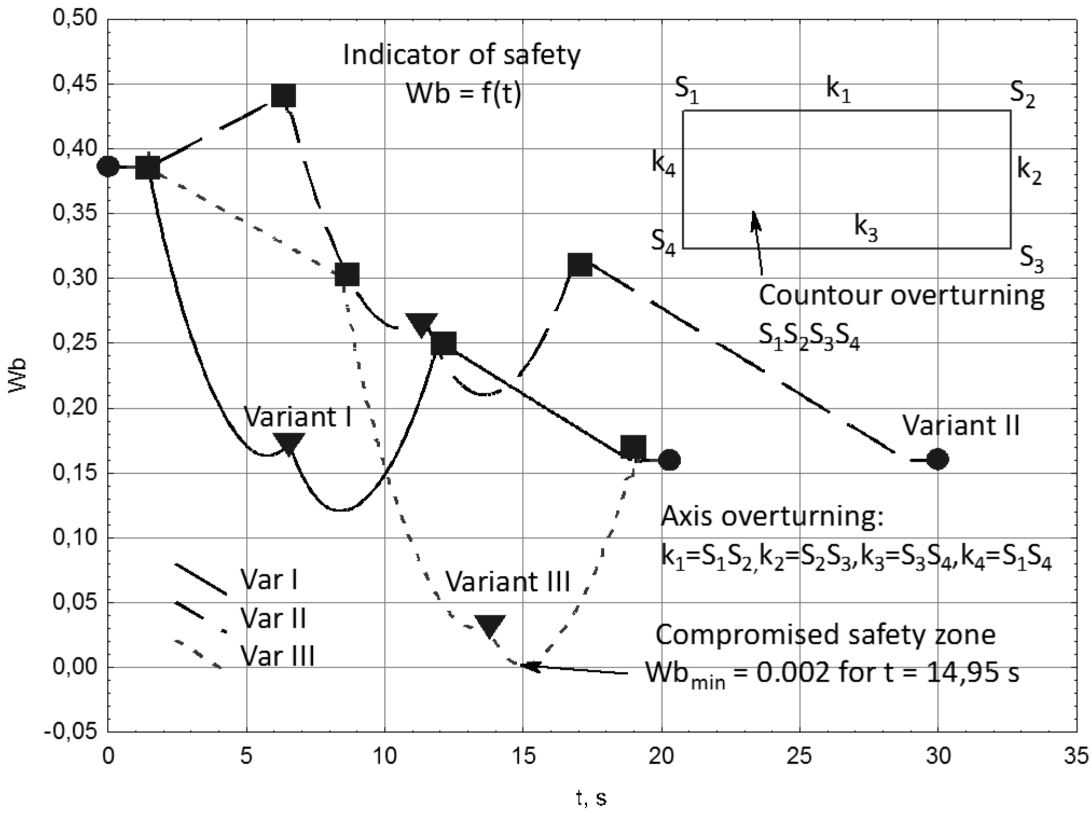


Fig. 7. Courses of the value of the safety indicator *Wb* for the three variants of the handling assignment, where: ● - start and end of movement, □ - start and end of circular motion, ∇ - change of the tip-over axis from $k_1$ to $k_2$

The trajectories presented in Fig. 6 that are determined by the gravity centres $Wu(x_{Wu}, z_{Wu})$ of the crane system are located inside the tip-over outline $S_1S_2S_3S_4$ (detail C); hence, stability conditions are met. This is confirmed by the courses of the formation of the value of the safety indicator *Wb* that are presented in Fig. 7. It is evident for the handling assignment example presented that the minimum value of the safety indicator for all of the three cases is greater than 0; hence, the crane system is stable over the whole range. For the third variant of the handling assignment, however, the value of this indicator $Wb = 0.002$ is very small. This means that for the trajectory of the load carried $\tau_H$ the working conditions are the least favourable as there is a risk of a loss of the crane system stability. This is confirmed with the diagrams from Fig. 8.

By analysing the courses presented, it can be found that in spite of ensuring the crane's static stability, there may occur a risk to its operation (Fig. 7: variant III). In the time interval between the 14th and 16th second, the values of the horizontal reaction force $Ry_{min}$ (Fig. 7a) and the torque differences $\Delta M$ (Fig. 7b) are the lowest. The gravity centre $Wu$ (Fig. 7) is located too close to the tip-over axis $S_1S_4$: as little as in the distance of $d = 0.34$ m.

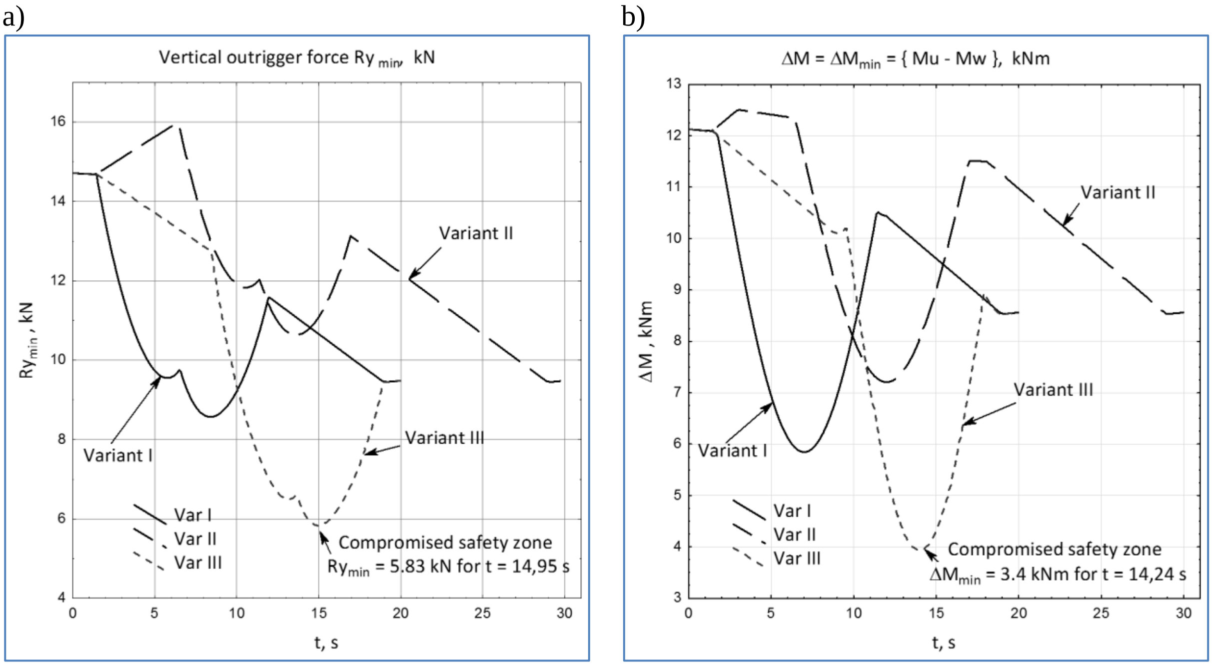


Fig. 8. Changes to the value of the base vertical reaction forces min($Ry_i$) (a) and values $\Delta M_{min}$ (b) during displacement of the cargo for the three variants of handling assignment

## 5. CONCLUSION

The article presents the method for efficiency assessment of the crane handling system for various load conditions and different cargo displacement trajectories with the use of modern CAD/CAE computing techniques. The developed simulation model, based on the example of a mobile crane type HDS HIAB XS111, allows to calculate variable configuration systems of the crane in the Cartesian space, positions of mass centres of the crane system, reactions and moments interacting with the outrigger system and the path length of the cargo transported.

Owing to the results of numerical simulation that meet stability conditions, it is possible to determine the optimum trajectory of the cargo displacements for the selected handling assignment. In optimization procedures, where the minimization of the path or handling time is the objective function, the values that determine the crane stability are constraining conditions. The use of the corrections of the displacements of the moving elements of the crane may prevent the outriggers from being broken off, and hence it allows fully safe operation in any conditions.

*This project is financed by the National Centre for Research and Development, Poland (NCBiR), under the Applied Research Programme - Grant agreement No. PBS3/A6/28/2015.*

**References**

1. Kacalak, W. & Budniak, Z. & Majewski, M. Computer aided analysis of the mobile crane handling system using computational intelligence methods. *Advances in Intelligent Systems and Computing*. 2018. Vol. 662. P. 250-261.
2. Kacalak, W. & Budniak, Z. & Majewski, M. Analiza stateczności żurawia dla różnych stanów obciążeń i różnych przemieszczeń ładunku. *Mechanik*. 2016. No. 12. P. 1820-1823. [In Polish: Crane stability for various load conditions and trajectories of load translocation].
3. Kacalak, W. & Budniak, Z. & Majewski, M. Model symulacyjny żurawia samojezdnego z zapewnieniem jego stateczności. *Modelowanie inżynierskie*. 2016. Vol. 29. No. 60. P. 35-43. [In Polish: Simulation model of a mobile crane with ensuring its stability. *Engineering modeling*].
4. Cekus, D. Modelowanie i badania symulacyjne ruchu żurawia laboratoryjnego. *Systems. Journal of Trandisciplinary Systems Science*. 2012. Vol. 16. No. 2. P. 96-103. [In Polish: Simulation research of the laboratory truck crane].
5. Herbin, P. & Pajor, M. Modelowanie kinematyki prostej i odwrotnej żurawia samochodowego o strukturze redundantnej z wykorzystaniem środowiska Matlab. *Modelowanie Inżynierskie*. 2016. Vol. 27. No. 58. P. 44-50. [In Polish: Simulation of interactions between mechanical and hydraulic system of loader crane. *Engineering modeling*].
6. Trąbka, A. The influence of clearances in a drive system on dynamics and kinematics of a telescopic crane. *Acta Mechanica et Automatica*. 2015. Vol. 9. No.1. P. 9-13.
7. Abdel-Rahman, E.M. & Nayfeh, A.H. & Masoud, Z.N. Dynamics and control of cranes. *Journal of Vibration and Control*. 2003. Vol. 9. No. 7. P. 863-908.
8. Arena, A. & Lacarbonara, W. & Casalotti, A. Payload oscillations control in harbor cranes via semi-active vibration absorbers: modeling, simulations and experimental results. *Procedia Engineering*. 2017. Vol. 199. P. 501-509.
9. Posiadała, B. Modelowanie identyfikacja modeli i badania dynamiki żurawi samojezdnych. WNT. Warszawa 2005. 212 p. [In Polish: Modelling and identification of models and tests of dynamics of mobile cranes. WNT Warsaw].
10. Geisler, T. Analiza statyczna ustroju nośnego żurawia samochodowego DST-0285. *Przegląd Mechaniczny*. 2012. No. 7-8. P.42-48. [In Polish: Static analysis of the truck crane structure DST-0285. *Mechanical Review*].
11. Posiadała, B. & Warys, P. & Cekus, D. & Tomala, M. The dynamics of the forest crane during the load carrying. *International Journal of Structural Stability and Dynamics*. 2013. Vol. 13. No. 7. P. 1-9.
12. Anezirisa, O.N. & Papazoglou, I.A. & Mud, M.L. & et al. Towards risk assessment for crane activities. *Safety Science*. 2008. Vol. 46. No. 6. P. 872-884.
13. Janusz, J. & Kłosiński, J. Wpływ wybranych strategii sterowania ruchami roboczymi żurawia samojezdnego na jego stateczność. *Acta Mechanica et Automatica*. 2010. Vol.10. No. 2. P. 74-80. [In Polish: Influence of the selected control strategies of mobile crane motions on its stability].
14. Kłosiński, J. & Janusz, J. Control of Operational Motions of a Mobile Crane under a Threat of Loss of Stability. *Solid State Phenomena*. 2009. Vol. 144. P. 77-82.
15. Lei, Z. & Taghaddos, H. & Han, S. & Bouferguene, A. & Al-Hussein, M. & Hermann, U. From AutoCAD to 3ds Max: An automated approach for animating heavy lifting studies. *Canadian Journal of Civil Engineering*. 2015. Vol. 42. No. 3. P. 190-198.
16. Posiadała, B. & Waryś, P. Modelowanie i badania symulacyjne ruchu żurawia leśnego w cyklu roboczym. *Modelowanie inżynierskie*. 2011. Vol. 10. No. 41. P. 331-338. [In Polish: Modeling and simulation research of forest crane in operating cycle. *Engineering modeling*].
17. Rauch, A. & Singhose, W. & Fujioka, D. & Jones, T. Tip-over stability analysis of mobile boom cranes with swinging payloads. ASME. *Journal of Dynamic Systems, Measurement and Control. Transactions of the ASME*. 2013. Vol. 135. No. 3. P. 031008–031008-6.
18. Sochacki, W. The dynamic stability of a laboratory model of a truck crane. *Thin-Walled Structures*. 2007. Vol. 45. No. 10-11. P. 927-930.
19. Urbaś, A. Analysis of flexibility of the support and its influence on dynamics of the grab crane. *Latin American Journal of Solids and Structures*. 2013. Vol.10. No. 1. P. 109-121.
20. Jeng, S.L. & Yang, C.F. & Chieng, W.C. Outrigger force measure for mobile crane safety based

on linear programming optimization. *Mechanics Based Design of Structures and Machines*. 2010. No. 38. P. 145-170.
21. Suwaj, S. & Mączyński, A. Sprawdzanie stateczności żurawia w trakcie realizacji ruchów roboczych. *Transport przemysłowy*. 2002. Vol. 4. No. 10. P. 26-29. [In Polish: Stability inspection of a crane during working movements. *Industrial Transport*].
22. Arena, A. & Casalotti, A. & Lacarbonara, W. & Cartmell, M.P. Dynamics of container cranes: three-dimensional modeling, full-scale experiments, and identification. *International Journal of Mechanical Sciences*. 2015. No. 93, P. 8-21.
23. Lee, J.S. & Shim, J.J. & Han, D.S. & Han, G.J. & Lee, K.S. An experimental analysis of the effect of wind load on the stability of a container crane. *Journal of Mechanical Science and Technology*. 2007. Vol. 21. No. 3. P. 448-454.
24. Lee, J.S. & Kang, J.H. Wind load on a container crane located in atmospheric boundary layers. *Journal of wind engineering and industrial*. 2008. Vol. 96, No. 2. P. 193-208.
25. Arena, A. & Casalotti, A. & Lacarbonara, W. & Cartmell, M.P. Three-dimensional modeling of container cranes. In: *Proc. of the Int. Design Engineering Technical Conf. and Computers and Information in Engineering Conf.* ASME. 2013. P. 1-9.
26. ISO 4305:2014 - Mobile cranes - Determination of stability.
27. PN-ISO 4304:1998. *Żurawie samojezdne, Wyznaczanie stateczności*. Warszawa: Polski Komitet Normalizacyjny. [In Polish: Self-propelled cranes. Determination of stability. Warsaw: Polish Committee of Standardization].
28. PN-ISO 4305:1998, *Dźwignice. Żurawie samojezdne. Wyznaczanie stateczności*. Warszawa: Polski Komitet Normalizacyjny. [In Polish: Cranes. Self-propelled cranes. Determination of stability. Warsaw: Polish Committee of Standardization].
29. Rupar, D. & Hladnik, J. & Jerman, B. Loader crane inertial forces. *FME Transactions*. 2016. Vol. 44. No. 3. P. 291-297.
30. Majewski, M. & Kacalak, W. Conceptual design of innovative speech interfaces with augmented reality and interactive systems for controlling loader cranes. *Advances in Intelligent Systems and Computing*. 2016. Vol. 464. P. 237-247.
31. Majewski, M. & Kacalak, W. Intelligent speech interaction of devices and human operators. *Advances in Intelligent Systems and Computing*. 2016. Vol. 465. P. 471-482.
32. Majewski, M. & Kacalak, W. Human-machine speech-based interfaces with augmented reality and interactive systems for controlling mobile cranes. *Lecture Notes in Computer Science*. 2016. Vol. 9812. P. 89-98.
33. Majewski, M. & Kacalak, W. Intelligent speech-based interactive communication between mobile cranes and their human operators. *Lecture Notes in Computer Science*. 2016. Vol. 9887. P. 523-530.
34. Majewski, M. & Kacalak, W. Innovative intelligent interaction systems of loader cranes and their human operators. *Advances in Intelligent Systems and Computing*. 2017. Vol. 573. P. 474-485.
35. Majewski, M. & Kacalak, W. Smart control of lifting devices using patterns and antipatterns. *Advances in Intelligent Systems and Computing*. 2017. Vol. 573. P. 486-493.
36. Majewski, M. & Kacalak, W. & Budniak, Z. & Pajor, M. Interactive control systems for mobile cranes. *Advances in Intelligent Systems and Computing*. 2017. Vol. 661. P. 10-19.

Received 19.10.2015; accepted in revised form 05.12.2017