RIGA TECHNICAL UNIVERSITY

Agrita KOVAĻSKA

USING METAMODELING FOR THE ANALYSIS AND OPTIMIZATION OF DYNAMIC SYSTEMS

Summary of Thesis

Riga 2012

RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
Institute of Mechanics

Agrita KOVAĻSKA
Candidate for a doctor's degree in the program „Mechanical engineering"

USING METAMODELING FOR THE ANALYSIS AND OPTIMIZATION OF DYNAMIC SYSTEMS

Summary of Thesis

Scientific adviser
Dr. sc. ing., professor, LZA corresponding member
J.AUZIŅŠ

Riga 2012

UDK 519.242 (043.2)
Ko 946 u

Kovaļska A. Using metamodeling for the analysis and optimization of dynamic systems. Abstract for the doctoral thesis.- R.:RTU, 2012.-24 pages.

Printed according with the 4th October, 2011 resolution of the Mechanics institute, protocol No. 4

The thesis has been developed with the support of the project "Support for the implementation of RTU doctoral studies – 2", cofinanced by the Europe Social Fund (ESF)

ISBN …………

THE DOCTORAL THESIS IS PROMOTED FOR OBTAINING THE ENGINEERING SCIENCE DOCTOR'S DEGREE IN THE RIGA TECHNICAL UNIVERSITY

The doctoral thesis for obtaining the engineering science (architecture, chemistry, economics, physics) doctor's degree will be publicly presented on 26th October, 2012, in the Faculty of Mechanics of the Riga Technical University, Ezermalas street 6, room 302

OFICIAL REVIEWERS

1. Professor, Dr. habil. sc. ing. Jānis Vība, Riga Technical University
2. Docent, Dr. sc. ing. Oscar Onzev, University „Turība"
3. Professor, Dr. sc. ing. Alexandr Koryakin, Riga Technical University

CONFIRMATION

I confirm that I have developed this doctoral thesis that has been submitted for reviewing to the Riga Technical University in order to obtain the engineering sciences doctor's degree. The doctoral thesis has not been submitted to any other university with the goal of obtaining a scientific degree.

Agrita Kovaļska …………………………….(Signature)

Date: ………………………

The doctoral thesis has been prepared in the Latvian language, it contains an introduction, 5 sections, conclusions, list of references, 64 drawings and illustrations, in total 123 pages. The list of references includes 85 titles.

CONTENTS

GENERAL DESCRIPTION OF THE THESIS

Topicality of the theme

Metamodeling is a new scientific current in the theoretical and experimental engineering science and mechanics. This method allows obtaining information about the structure of the investigated object by analyzing solely the registered output measurements of this object (machine, mechanism, technological process), and identifying both the mathematical model of the object and its input parameter values, using both natural experiments and computer experiments with different mathematical modeling software (ANSYS, ADAMS, LSDYNA etc.). It is particularly important to develop and verify the metamodeling methodology for dynamical processes where the experiment responses are time functions rather than numbers.

The subject of the thesis is related with the earlier research conducted by the scientists of the Scientific laboratory for Machine and mechanism dynamics problems of the Riga Technical University Institute of Mechanics for the Ministry of Education and Science, Latvian Council of Science and international EU 6th and 7th framework programs scientific projects (Aurora, COCOMAT, INTERSHIP, FRIENDCOPTER, etc.).

Working on the thesis required the further developing of the methodology of experimental mechanics and modeling created in the RTU, applying it to the analysis of construction material production – the vibropressing technology of concrete forming, and the optimization of its various elements.

The goal of the paper

The goal of the doctoral thesis is the development of experimental optimization methodology for dynamic systems, applying it to the concrete vibropressing technology.

Research tasks

1. Development of experimental optimization methodology for dynamic systems.
    - 1.1. Approximation of the response function for dynamic processes.
    - 1.2. Creation of optimal experiment designs.
    - 1.3. Creation of metamodels for the dependence of the response function to the input factors.
    - 1.4. Multicriterion optimization.
2. Applying the developed methods to concrete vibropressing technology.
    - 2.1. Creation of a simplified metamodel for the vibropressing compacting process (description of the curve with 3 parameters).
    - 2.2. Creation of an experimental device, conducting experiments.
    - 2.3. Creation of a full metamodel for the vibropressing process.
    - 2.4. Formulating the multiobjective optimization goal functions and constraints, conducting optimization..
    - 2.5. Verification and validation of results.

The scientific novelty of the thesis

Working on the thesis requires the further developing of the methodology of experimental mechanics and modeling created in the RTU, applying it to the analysis of construction material production – the vibropressing process of concrete forming.

The practical value of the thesis

The further application of the developed methodology for the dynamic optimization of various mechanical systems, including vehicle elements. It is relatively simple to analyze and optimize a dynamical process (transitional process or stationary mode), using the metamodeling approach on the basis of the algorithm developed in this paper (Fig. 5). For example, a similar approach may be employed for such dynamic processes as the automobile braking process (choosing the automobile mass, initial speed and friction coefficient as the input data, and the braking trajectory as the output), the aerodynamics of a bullet leaving the barrel (using the bullet mass, dimensions, shooting speed as input data and the flight trajectory as the output data), etc. A methodology of this type allows significantly shortening the time required for design and helps in perceiving the essence of the dynamical process.

The presentation includes

- The developed metamodeling methodology for the analysis of dynamical systems which includes:
  1) creating a simplified model for the dynamic transition process with a finite number of parameters,
  2) choosing the input factors for the dynamic process,
  3) creating and conducting experimental designs for natural and numerical experiments,
  4) creating the process metamodel, using parametrical and non-parametrical approximation methods,
  5) conducting the multiobjective optimization of the process,
  6) verification and validation of results.
- Application of the methodology to the analysis and optimization of the concrete vibropressing process.
- Metamodels created for the dynamic (vibropressing) process forming relationships.
- Metamodels created to describe the dependence of the compacting process parameters on the parameters of the technological process.
- Using the metamodeling approach, the multiobjective optimization of the vibropressing process was carried out.
- An algorithm for applying metamodeling to the analysis and optimization of dynamic systems

Publications

1. Auzins J., Janushevskis A., Kovalska A.,Ozoliņš O. „Experimental Identification and Optimization of the Concrete Block Vibropressing Process*". Journal of Vibroengineering,* Vol.**12**, Issue 3. (2010) 1.-12. lpp.

2. Auziņš J., Januševskis A., Kovaļska A., Meļņikovs A., Ozoliņš O. „Vibrotriecienpreses ģeometriskā un aprēķinu modeļu izstrāde". *RTU Zinātniskie raksti, Mašīnzinātne un transports*. – ISSN 1407-8015, 6.sērija, 28. sējums, 2008., 63. – 77. lpp.

3. Auziņš J., Januševskis J.,Kalniņš K., Kovaļska A. „Optimization and Metamodeling of Metal Sandwich Panel Structures*"; RTU Zinātniskie raksti, Mašīnzinātne un transports*. – ISSN 1407-8015, 6.sērija, 33. sējums, 2010., 83. – 88. lpp.

4. Auziņš J., Boiko A., Januševskis A., Januševskis J., Kovaļska A., Meļņikovs A., Pfafrods J. „Development of Methods and Tools for Simulation, Identification and Multiobjective Optimization of Mechanical Systems at the Machine and Mechanism Dynamics Laboratory" *RTU Zinātniskie raksti, Mašīnzinātne un transports*. – ISSN 1407-8015, 6.sērija, 31. sējums, 2009., 19. – 26. lpp.

5. Kovaļska A. „Beramu materālu vibropresēšanas procesa strukturālā identifikācija un optimizācija" *RTU Zinātniskie raksti*, Mašīnzinātne un transports, Rīga 2011. Apstiprināts publicēšanai.

6. Auziņš J., Kovaļska A. „The effect of vibropressing process on the strength of concrete” *16th International Conference Mechanika – 2011*, Lietuva, Kauņa, 7.-8. aprīlis, 2011, Mechanika: Proceedings of 16th International Conference, 19.-23. lpp.

7. Auzins J., Kovalska A. „The investigation of vibropressing process technology” *10th International Scientific Conference “Engineering for Rural development”*, Latvija, Jelgava, 26.-27. maijs, 2011, 10th International Scientific Conference “Engineering for rural development. Proceedings, Volume 10.,. 408.-412. lpp.

8. Auzins J., Kovalska A. „Computational dynamic analysis of raw concrete vibropressing process” Vibration Problems ICOVP 2011, Supplement, The 10th biennial International Conference on Vibration Problems, 5.-9. sept. 2011., 192.-198. lpp.

9. Auzins J., Janushevskis A., Kovalska A, Ozolins O. „Experimental identification and optimization of concrete block vibropressing process” *Proceedings of WCSMO-8 Eight World Congress on Structural and Multidisciplinar Optimization*, 1-5 June 2009, Lisboa, Portugal, CD-ROM edition, 10 pages

Approbation

The results of the doctoral thesis were notified and discussed in scientific conferences and regularly presented in the LNMK scientific seminārs:

1. J. Auzins, A. Janushevskis, A. Kovalska, O. Ozolins Experimental identification and optimization of concrete block vibropressing process. WCSMO-8 *Eight World Congress on Structural and Multidisciplinar Optimization*, 1-5 June 2009, Lisboa, Portugal

2. J. Auziņš, A. Januševskis, A. Kovaļska, O. Ozoliņš „Experimental Identification and Optimization of the Concrete Block Vibropressing Process” VIBROENGINEERING 2009, *8th INTERNATIONAL CONFERENCE*, September 16-18,2009, H. Manto str.84, LT-92294, Klaipeda University Klaipeda, Lithuania

3. J. Auziņš, J. Januševskis, A. Kovaļska „Vienas mehāniskās sistēmas parametru optimizācija”, Sekcija «Ražošanas tehnoloģija un transports» Apakšsekcija " Inženiertehnika, mehānika un mašīnbūve", *RTU 50. Starptautiskā zinātniskā konference*, 16.oktobris, 2009., Ezermalas-6, Rīga, Latvija

4. J. Auziņš, A. Januševskis, A. Kovaļska “Experiemental identification and multiobjective optimization of vibrocompacting process of composite substances, *Mechanics of composite materials*, 24 - 28. maijs, 2010. g., Jūrmala, Latvija

5. A. Kovaļska RTU, „Beramu materālu vibropresēšanas procesa strukturālā identifikācija un optimizācija” *RTU 51. Starptautiskā zinātniskā conference*, 11.-15. oktobris, 2010.g., Rīga, Latvija

6. J. Auzins, A. Kovalska “The effect of vibropressing process on the strength of concrete” *16th International Conference Mechanika 2011,* 7 - 8 April, 2011 Kaunas, Lithuania

7. A. Kovalska, J. Auzins “The investigation of vibropressing process technology” *10th International Scientific Conference Engineering for Rural Development*, 26 - 27 May, 2011, Jelgava, Latvia

8. A. Kovalska, J. Auzins „Computational dynamic analysis of raw concrete vibropressing process” *Vibration problems – ICOVP 2011, International Conference On Vibration Problems 2011*, Technical University of Liberec, 5 – 9 September, 2011, Liberec, Czeck Republic

9. A. Kovaļska, disertācijas aprobācija pirms tās aizstāvēšanas ar nosaukumu: „METAMODELĒŠANAS PIELIETOJUMS DINAMISKU SISTĒMU ANALĪZĒ UN OPTIMIZĀCIJĀ", *RTU Mehānikas institūta Mehānikas seminārs,* 4. oktobris, 2011.g., RTU, MEHĀNIKAS INSTITŪTS, Latvija, Rīga, Ezermalas iela 6.

10. A. Kovaļska „Beramu materiālu vibropresēšanas procesa strukturālā identifikācija un optimizācijas kritēriji” *Apvienotais Pasaules latviešu zinātnieku III kongress un Letonikas IV kongress „Zinātne, sabiedrība un nacionālā identitāte”* Rīgā, 24.-27. oktobris, 2011. g., Apakšsekcija „Mehānika un mašīnbūve”, Stenda referāts, Rīgas Tehniskā universitāte.

CONTENT OF THE PAPER

In the first section information is summarized about the metamodeling methodology [1, 8, 10, 11, 17], including experiment design and analysis [2, 3, 5, 6, 12, 16], reviewing several approximation techniques [2, 3, 7, 9, 16, 17]. The optimization methodology and formulation of the optimization task is discussed [2, 4, 13, 14, 15, 18], as well as the solution possibilities for the multicriterion optimization [13, 14, 15]. The concrete sample forming vibromolding process is used as the dynamic system which is analyzed by applying the metamodeling methodology. The exogenous parameters of the reviewed dynamic system are manageable, while the endogenous parameters contain random dispersion.

In order to provide an introduction to the character of the researched material of the dynamic system, a short review of the structure and properties of concrete is given [19, 20].

In the second section a metamodel is created for the vibromolding process, as well as an experimental design. To implement the experimental design, it was necessary to design and create experimental equipment using the SolidWorks software, which was also included in this section. The concrete mortar content is determined for all further experiments. While conducting the experiment, all the experiment measurement data was gathered and compiled in tables. The concrete samples were first formed, changing the vibropressing process parameters according to the developed experiment design, repeating each attempt at least three times, then after 28 days these samples were demolished. Then all the data obtained during the experiment was processed with the goal of eliminating the results that contain large errors. The values of the measurements containing large errors were significantly different from the other measurements.

The strength values of the selected samples after the processing of the results allow a more precise determination of the samples that were formed by identical vibropressing process parameters. These were the values that were used as a basis for further development of the methodology for the metamodeling and optimization of the concrete block vibropressing process.

In this section the first phase for the methodology of applying metamodeling to analysis of dynamic systems was developed. The algorithm for the phase of the methodology developed in this section is shown in the figure 1.

In the second section the input and output factors of the experiment are chosen, the experimental device is created and the screening of experiments is carried out.

The first phase of the developed methodology includes the verification and validation of the results in case of necessity, to obtain improved precision. It is

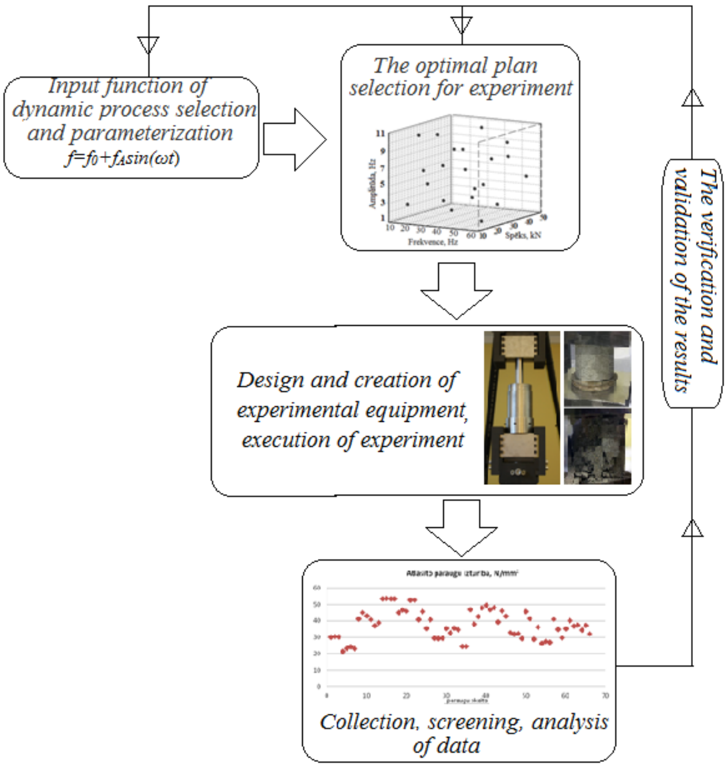

Fig. 1. Algorithm for the phase of the methodology developed in this section

possible that improvements for the creation of the approximation model are necessary, as well as changes and additions in the experiment design.

In the third section, on the basis of the obtained experimental data a response function metamodel is created for the dynamic process (figure 2).

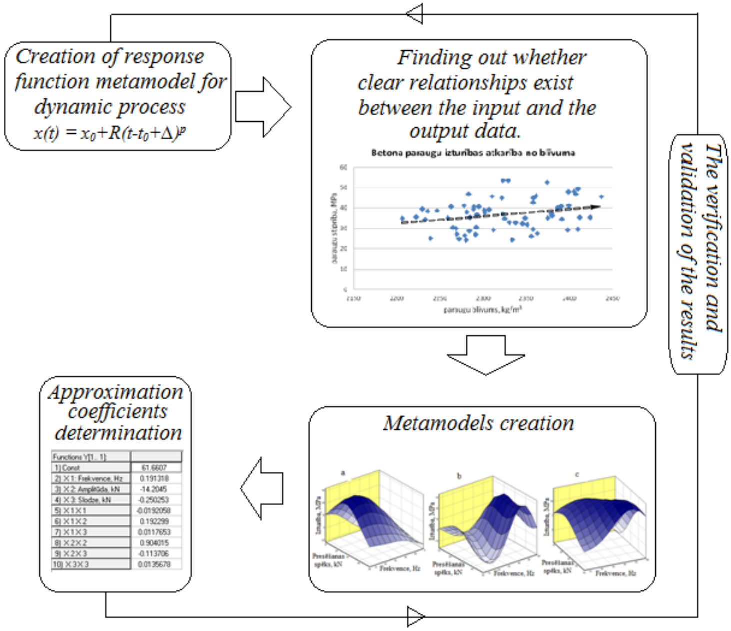

Fig. 2. Algorithm for the phase of the methodology developed in this section

Afterwards the influence of each vibropressing process variable parameter on the strength of the obtained samples is reviewed to form an idea of the character of the process itself and to find out whether clear relationships exist between the input and the output data.

Using the EDAOpt software [2], metamodels have been created for the dependence of the sample strength on the compacting process parameters according to the polynomial regression quadratic and Kriging approximation methods; the results were compared with each other, taking into account the value of the crossvalidation error for the Kriging approximation – 7.3%, and the polynomial regression crossvalidation error – 25.6%. Using the Mathcad software, the quality of the adjustment of the polynomial regression quadratic approximation metamodel [16] was verified for the obtained data according to the Fischer criterion.

The approximation coefficients necessary for further multiobjective optimization were determined.

The algorithm for the phase of the methodology developed in this section is shown in figure 2.

In the fourth section, on the basis of the characteristic parameters of the chosen dynamic process and bearing in mind the characteristics of the vibropressing process, the goal functions and boundaries of the multiobjecive optimization were determined. In order to optimize the vibropressing process, the following criteria are proposed:

1. Process duration, (t, s) → *min*;
2. Consumed energy, (W, J) →*min;*
3. Compacting characteristic parameter, (C_r, mm) → *max*;
4. Molding force f_0 → *min;*
5. Sample strength after 28 days, *P (MPa*) →*max;*
6. Product costs (*Ls*) →*min;*

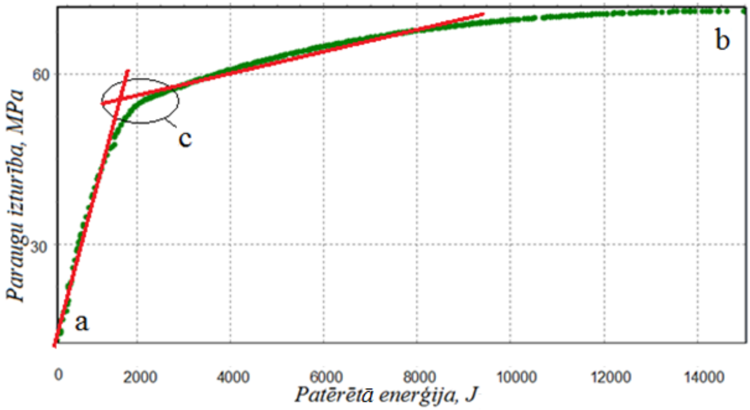

Fig. 3. Pareto frontier analysis

Using the EDAOpt software, the solutions for multiobjective optimization tasks were found in the Pareto frontier and Pareto surface [13, 14, 15] interpretation.

The section includes a Pareto frontier (Fig. 3) and surface analysis. Analyzing figure 3, we may observe that the obtained Pareto frontier dramatically changes its slant in the *c* region, it becomes flatter. It is precisely in this region that a strength of concrete samples may be obtained that is equal to approximately 55 MPa – which is about 44% greater than the average value of the samples, without consuming an amount of energy exceeding 2000 J in the given case.

The algorithm for the methodology developed in this section is given in Figure 4. This algorithm also includes result verification and validation, if it is necessary to improve, make more accurate or modify the goal functions and boundaries.

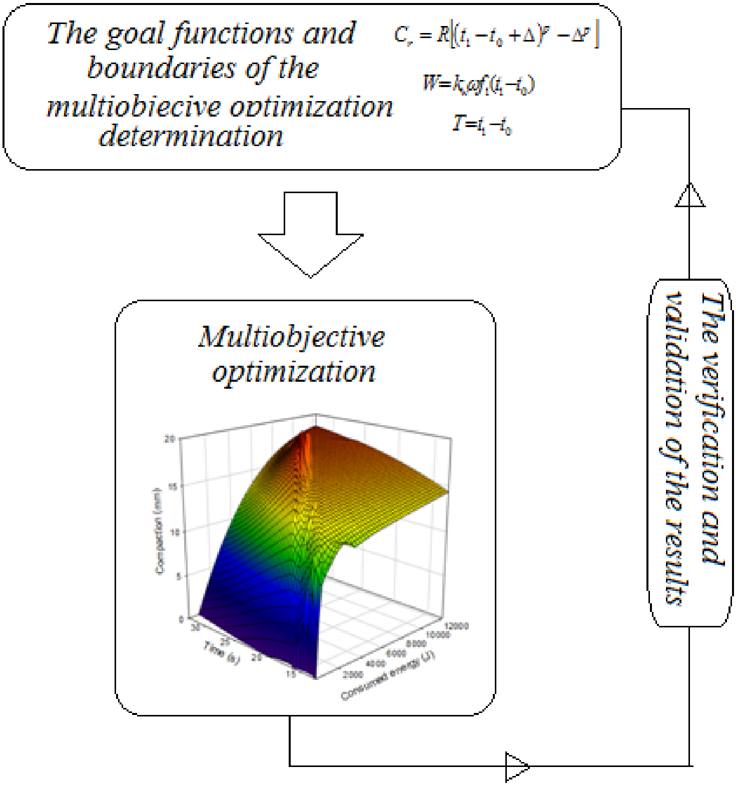

Fig. 4. Algorithm for the phase of the methodology developed in this section

In the fifth section a total definition is given for the methods of applying metamodeling to the analysis and optimization of dynamic systems. An algorithm of the methodology (Fig. 5) is created in the form of a block diagram, on the basis of the previous sections, and the process of the developed methodology is described.

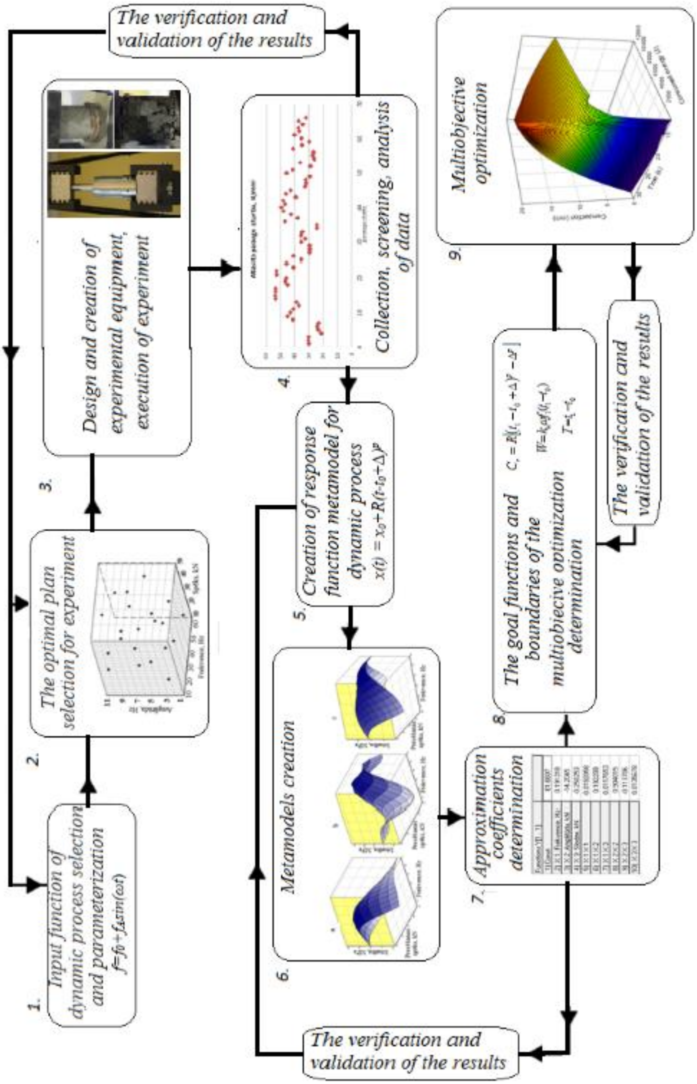

Fig. 5. Algorithm for applying metamodeling to the analysis and optimization of dynamic systems

CONCLUSIONS

1. The doctoral thesis includes a comprehensive literature analysis in the fields of dynamic system metamodeling, experiment design and analysis, multiobjective optimization, as well as the technological processes of high durability concrete forming.

2. The metamodeling methodology for the analysis of dynamic systems has been developed, including 1) creating a simplified model for the dynamic transition process with a finite number of parameters, 2) choosing the input factors for the dynamic process, 3) creating and conducting experimental designs for natural and numerical experiments, 4) creating the process metamodel, using parametrical and non-parametrical approximation methods, 5) conducting the multiobjective optimization of the process, 6) verification and validation of results.

3. The methodology has been applied to the analysis and optimization of the concrete vibropressing process.

4. Concrete vibropressing experiments have been carried out with material dynamic testing equipment, and the strength of the samples has been determined.

5. Metamodels have been created for the dynamic (vibropressing) process forming relationships.

6. Metamodels have been created to describe the dependence of the compacting process parameters on the parameters of the technological process.

7. Using the metamodeling approach, the multiobjective optimization of the vibromolding process was carried out – as a result, it is possible to understand what is the minimal energy consumption required to achieve sample strength that is 44% greater than the average sample strength value.

8. Further directions of work – developing the metamodeling methodology for other dynamic processes where the experiment responses are stationary and non-stationary processes.

LIST OF REFERENCES

[1]Atkinson C., Kühne T., "Model-Driven Development: A Metamodeling Foundation" IEEE Software, vol. 20, no. 5, Sep/Oct, 2003, p. 36-41

[2] Auzins J. (2004). Direct optimization of experimental designs. Proc. of 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization conf ., Albany, NY, 2004, CD edition, AIAA paper No: 2004-4578

[3] Auzins J., Janusevskis A. (2007). Eksperimentu plānošana un analīze, Rīga, RTU, ISBN 97-9984-32-157-8

[4] Audze P. and Eglājs V. (1977). New approach to the design of multifactor experiments. Problems of Dynamics and Strengths 35, Zinatne Publishing House, Riga, 104-107

[5] Bézivin, J., "In Search of a Basic Principle for Model Driven Engineering," Upgrade, vol. 5, no. 2, 2004, p. 21-24

[6] Butler N. A. (2001). Optimal and Orthogonal Latin Hypercube Designs for Computer Experiements. Biometrika 88, 847-857

[7] Cleveland W. S., and Grosse E. (1991). Computational Methods for Local Regression. Statistics and Computing, 1, 47-62

[8] Djuric, D., Gaševic, D., Devedžic, V.,: "The Tao of Modeling Spaces", in Journal of Object Technology, vol. 5. no. 8, Novmeber-December 2006, pp. 125-147

[9] Fan J. and Gijbels I. (1996). Local Polynomial Modelling and Its Applications. Chapman & Hall, London

[10] Janushevskis, J. Auzins, T. Akinfiev, A.Boyko, A comparative analysis of global search procedures Proc. Estonian Acad. Sci. Eng., 2004, Vol.10, No.4, 235-250

[11] Januševskis J. Metamodelēšanas metožu izstrāde un pielietojums mehānisku sistēmu analīzē un optimizācijā, disertācija, Rīga, 2008

[12] Koehler J. R. and Owen A. B. (1996). Computer experiments. In Handbook of Statistics,Vol. 13., eds. S. Ghosh and C. R. Rao., Elsevier, p. 261-308.

[13] Marler R.T., Arora J.S. Survey of multi-objective optimization methods for engineering Struct Multidisc Optim 26, 369–395 (2004)

[14] C. A. Mattson and A. Messac. Pareto frontier based concept selection under uncertainty, with visualization. Optimization and Engineering, 6(1):85–115, 2005

[15] Messac A.. Mullur A.,MULTIOBJECTIVE OPTIMIZATION: CONCEPTS AND METHODS OPTIMIZATION OF STRUCTURAL AND MECHANICAL SYSTEMS 2007 World Scientific Publishing Co. Pte. Ltd. 5 Toh Tuck Link, Singapore 59622

[16] Montgomery D. C. (2005), Design and Analysis of Experiments, 6th ed., John Wiley & Sons, New York

[17] Wang G., Shan S. (2007). Review of Metamodeling Techniques in Support of Engineering Design Optimization. Journal of Mechanical Design, Vol. 129, Issue 4, p. 370-380

[18] Yang K., Trewn J. Multivariate Statistical Methods in Quality Management. McGraw-Hill, 2004

[19] Ахвердов и.н. основы физики бетона Москва, Стройиздат, 1981, с.373

[20] Баженов Ю. М. «Технология бетона» © Издательство «Высшая школа», 1987, с изменениями http://bibliotekar.ru/spravochnik-176-tehnologia-betona/1.htm