Simulation of Behaviour Dynamics of the Ship Steam Boiler

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Abstract: - The aim of this paper is to demonstrate the successful application of system dynamics simulation modelling at investigating performance dynamics of the ship steam boiler. Ship steam boiler is a complex non-linear system which needs to be systematically investigated as a unit consisting of a number of subsystems and elements, which are linked by cause-effect (UPV) feedback loops (KPD), both within the system and with the relevant surrounding. In this paper the author will present the efficient application of scientific methods for the research of complex dynamic systems called qualitative and quantitative simulation System dynamics methodology, which will allow for production and use of higher number and kinds of simulation models of the observed elements, and finally allow for the continuous computer simulation, which will contribute to acquisition of new information about the non-linear character of performance dynamics of ship steam boilers in the process of designing and education.

Key-Words: - Ship steam boiler, simulation modelling, system dynamics, and simulation.

1 Introduction

The purpose of this paper is to present the efficiency of application of the system dynamics simulation modelling (System Dynamics Modelling–Jay Forrester – MIT) to the research of performance dynamics of complex non-linear marine propulsion systems. The ship boiler system is a complex non-linear system which needs to be systematically investigated as a whole, consisting of a number of subsystems and elements, which are linked by cause-effect (UPV) feedback loops (KPD), both within the propulsion system and with the relevant surroundings. The essential hypothesis of this paper is the author conviction that the ship steam boiler is a non-linear and very complex technical system with pronounced multiple, inter-causal connections and feedback loops dominating the performance of the relevant variables. Furthermore, the additional assumption is that these pronounced manifestations are so complex that only the application of the relatively newer scientific methodology of the system dynamics simulation modelling will eventually result in a higher level of insights into dynamic phenomena of transitional manifestations of the observed system, which will be confirmed, in both theoretical and practical ways, by the scientific comparison of simulation results with empirical measurements. Indirect methodologies, which have been used so far, do not meet present-day needs for insights into behaviour dynamics of non-linear ship systems. They have been based on using classical, mainly linearized methods such as Laplace's transformation, transient functions and stability criteria. Although System dynamics, as a scientific discipline, has been around for several decades, it was the high performance speed of modern digital computers, which increased the accuracy of simulation modelling, that has now allowed practical and simple application of the computer simulation of non-linear dynamic systems of higher level (whose models comprise thousands of differential equations), i.e. extremely complex systems. Over the last few years the dynamic simulation system has been used to a great extent during research of behaviour dynamics of all sorts of complex systems. The author of this paper believe that System dynamics is an excellent scientific tool for investigating behaviour dynamics of complex engine systems, sub-systems, and elements. System dynamics as a scientific discipline is actually a mathematical-computer-simulation methodological tool that serves as the basis of the general system theory and management theory. Given the high complexity of ship systems, this paper has presented the efficiency of application of a scientific method of investigating complex dynamic systems called *Qualitative and quantitative simulation methodology of System dynamics* (System Dynamics Modelling Approach – MIT), which has enabled designing and using a number of types of simulation models for an observed reality, and has finally enabled a continued computer simulation using fast and accurate digital computers. This has considerably contributed to acquiring new insights into the non-linear nature of performance dynamics of the boiler system in the process of designing and education. Simulation modelling, supported by System Dynamics and intensive use of modern digital computers, is one of the most appropriate and successful scientific methods of investigating performance dynamics of non-linear natural, technical and organisational systems. In the educational and design practice so far, the methodology of system dynamics (J. Forrester – MIT), as a relatively newer scientific discipline, proved to have been an efficient tool in the scientific research of the problems of management, behaviour, sensitivity and flexibility of numerous systems and processes, according to [1].

2. Simulation modelling of the ship steam boiler

2.1. Mathematical model of ship steam boiler

Studying thermodynamic behaviour of ship steam boiler may be, performed in such way that the steam boiler is observed as a heating capacity unit consisting of the following heating capacity elements, according to [2], [3], [4], [5] and [6]

- Metal parts of the boiler,
- Economisers,
- Quantity of water in the boiler and pipes,
- Quantity of dry saturated and overheated steam,
- Steam super heater.

The boiler may be considered as a homogenous device, a thermal accumulator, i.e. a homogenous thermal capacity. The equations of thermal balance of such thermal accumulator (capacity) suggest determining the equation for the level of the water in the boiler. In order to create equations of performance dynamics of the boiler it is necessary to observe only the steam piping part of the boiler (Fig. 1).

The following are brought to the steam piping:

1. Thermal power of the fuel which is brought to the burner of the boiler Q_G *[kJ/h]*,
2. Thermal power of the feed water which is brought to the boiler Q_{PV} *[kJ/h]*,
3. Thermal power of the steam which is discharged from the boiler Q_P *[kJ/h]*.

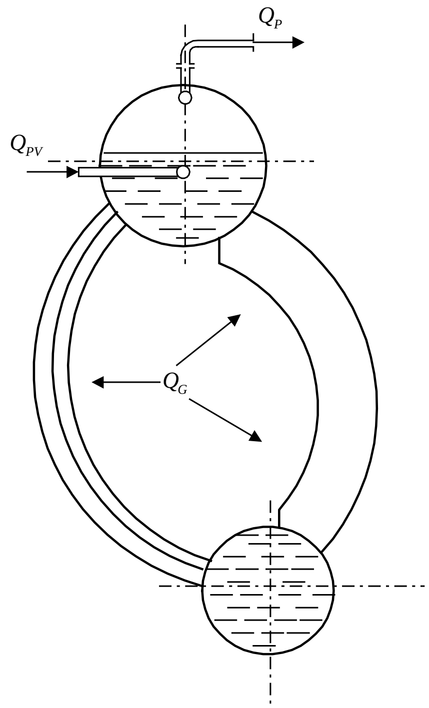

Fig. 1. Presentation of the steam boiler with natural circulation [7]

System dynamics mathematical model of the ship steam boiler is defined by explicit form of differential equations, according to [2]:

1. Equation of the boiler dynamics for the steam pressure:

$$\frac{d\varphi_K}{dt} = \frac{1}{T_{a1}} \cdot (\mu_G + a_1 \cdot \mu_V - a_2 \cdot \mu_P - a_3 \cdot \frac{d\mu_P}{dt} - k \cdot \varphi_K) \quad (1)$$

2. Equation of the boiler dynamics for the water level:

$$\frac{d\varphi_Y}{dt} = \frac{1}{T_{a2}} \cdot (\mu_V - b_1 \cdot \varphi_K - b_2 \cdot \frac{d\varphi_K}{dt} - b_3 \cdot \mu_P - b_4 \cdot \frac{d\mu_P}{dt}) \quad (2)$$

Where the following denote:

φ_K - relative state of the steam pressure in the boiler,

φ_Y - relative state of the water level in the boiler,

T_{a1} - time constant of the steam boiler for the steam pressure [s],

T_{a2} - time constant of the steam boiler for the water level [s],

k - coefficient of self-regulation of the steam boiler,

μ_G - relative change of the position of the fuel valve,

μ_V - relative change of the valve of the feed water,

μ_P - relative change of the position of the steam discharge valve,

$\frac{d\varphi_K}{dt}$ - speed of the change of the relative increment of the boiler steam pressure,

$\frac{d\mu_P}{dt}$ - speed of the relative change of the position of the steam discharge valve,

$a_{1,2,3}$ - coefficients of the steam boiler for the steam pressure,

$b_{1,2,3,4}$ - coefficients of the steam boiler for the water level.

2.2. System dynamics mental-verbal of the ship steam boiler

On the basis of a mathematical model, or the explicit form of the mode equation of the ship steam boiler (1) it is possible to determine the mental - verbal model of the ship steam boiler:

- If the relative increment of the steam pressure in the boiler φ_K increases, the speed of the change of the relative pressure in the boiler $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the speed of the change of the relative increment of the steam pressure $\frac{d\varphi_K}{dt}$ increases, the state of the relative increment of the steam pressure in the boiler φ_K will increase, which is the integral or sum of all changes of the state, which gives a positive cause-effect link (+).

In the observed circle of the cause-effect (KPD) there are only two cause-effect (UPV) links, and the sum of their negative values is 1, so the global sign for cause-effect KPD is negative, which means self-regulating, which leads any change of the state towards quiescent state, according to [8].

- If the coefficient of self-regulation of the steam boiler for the steam pressure k increases, the speed of the change of the relative increment of the steam pressure in the boiler $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the time constant of the boiler for the steam pressure T_{a1} increases, the speed of the change of the state of the relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the relative change of the position of the fuel supply valve μ_G increases, which assumes the increase of fuel supply in the time unit, the speed of the change of state of relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will increase, which gives a positive cause-effect link (+).
- If the auxiliary coefficient a_1 increases, the speed of the change of relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will increase, which gives a positive cause-effect link (+).
- If the relative change of the position of the feed water valve μ_V increases, the speed of the change of the relative state of the increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will increase, which gives a positive cause-effect link (+).
- If the auxiliary coefficient a_2 increases, the speed of the change of the state of the relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the relative change of the steam discharge valve μ_P increases, the speed of the change of the state of the relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the auxiliary coefficient a_3 increases, the speed of the change of state of the relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the speed of the relative change of the position of the boiler steam discharge valve $\frac{d\mu_P}{dt}$ increases, the speed of the change of the state of the relative increment of the boiler steam pressure $\frac{d\varphi_K}{dt}$ will decrease, which gives a negative cause-effect link (-).

- If the relative change of the position of the boiler steam discharge valve μ_P increases, the speed of the change of the relative change of the boiler steam discharge valve position $\frac{d\mu_P}{dt}$ will increase, which gives a positive cause-effect link (+).

On the basis of the mathematical model, or the explicit form of the equation of the ship steam boiler (2) it is possible to determine the mental - verbal model of ship steam boiler:

- Dynamic performance process of the steam boiler with natural circulation for the water level does not have self-regulating property, because there is no internal negative cause-effect link (KPD), which the dynamic process of steam boiler performance with natural circulation for the steam pressure has.

- If the time constant of the steam boiler for the water level T_{a2} increases, the speed of the change of the state of relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the relative change of the feed water valve position μ_V increases, the speed of the change of the relative increment of the steam boiler water level $\frac{d\varphi_Y}{dt}$ will increase, which gives a positive cause-effect link (+).
- If the auxiliary coefficient b_1 increases, the speed of the change of the state of the relative increment of the steam boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the relative increment of the boiler steam pressure φ_K increases, the speed of the change of the state of the relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the auxiliary coefficient b_2 increases, the speed of the change of the state of the relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the speed of the change of the relative increment of the steam pressure $\frac{d\varphi_K}{dt}$ increases, the speed of the change of the state of the relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the relative change of the position of the steam discharge valve μ_P increases, the speed of change of the state of the relative increment of boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the auxiliary coefficient b_3 increases, the speed of the change of the state of the relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the speed of the change of the relative position of the boiler steam discharge valve $\frac{d\mu_P}{dt}$ increases, the speed of the change of the state of the relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).
- If the auxiliary coefficient b_4 increases, the speed of the change of the state of the relative increment of the boiler water level $\frac{d\varphi_Y}{dt}$ will decrease, which gives a negative cause-effect link (-).

2.3. System dynamics structural models of the ship steam boiler

On the basis of the stated mental - verbal models it is possible to produce structural diagrams of the ship steam boiler, as shown in Figures 2, 3 and 4, according to [9], [10], [11], [12] and [13].

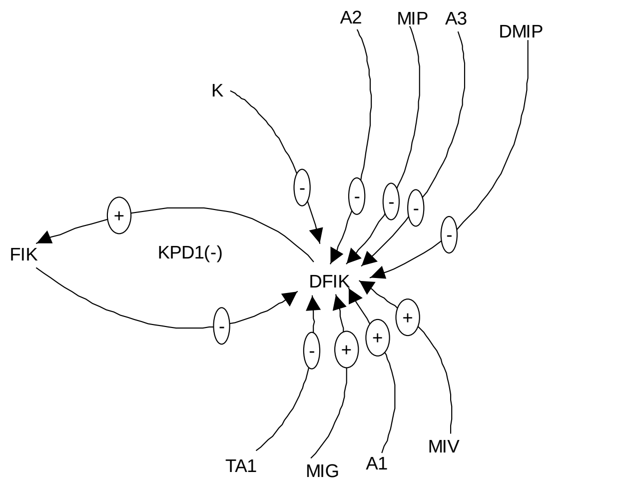

Fig. 2. Structural model of the ship steam boiler – for steam pressure

Where is:
FIK - relative state of the steam pressure in the boiler,
TA1- time constant of the steam boiler for the steam pressure [s],
K- coefficient of self-regulation of the steam boiler,
MIG- relative change of the position of the fuel valve,
MIV- relative change of the valve of the feed water,
MIP- relative change of the position of the steam discharge valve,
DFIK- speed of the change of the relative increment of the boiler steam pressure,
DMIP - speed of the relative change of the position of the steam discharge valve,
A1, A2, A3 - coefficients of the steam boiler for the steam pressure.

In the observed system there is the feedback loop (KPD1).
KPD1(-):FIK=>(-)DFIK=>(+)DFIK=>(+)FIK;
which has self-regulating dynamic character (-), because the sum of negative signs is an odd number.

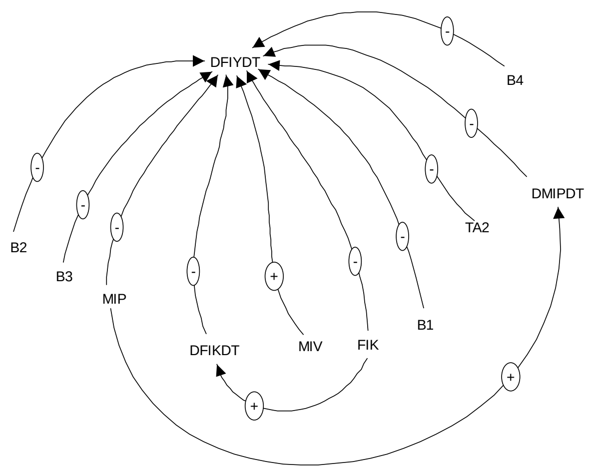

Fig. 3. Structural model of the ship steam boiler – for the water level

Where is:
FIK- relative state of the steam pressure in the boiler,
TA2- time constant of the steam boiler for the water level [s],
MIV- relative change of the valve of the feed water,
MIP- relative change of the position of the steam discharge valve,
DFIYDT- speed of the change of the state of relative increment of the boiler water level,
DFIK- speed of the change of the relative increment of the boiler steam pressure,
DMIP- speed of the relative change of the position of the steam discharge valve,
B1-4 - coefficients of the steam boiler for the water level.

In the observed system there is not a feedback loop KPD, because the dynamic process of the performance of the steam boiler with natural circulation for the water level does not have the self-regulation property.

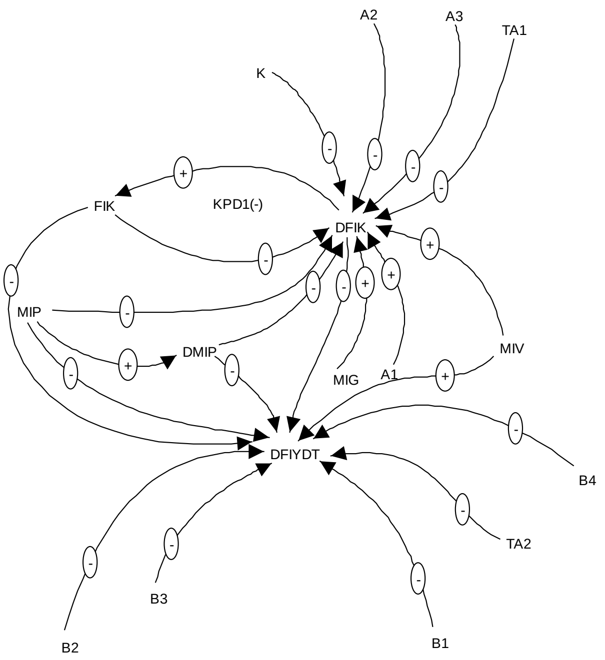

Fig. 4. Global structural model of the ship steam boiler

2. 4. System dynamics flowchart of the ship steam boiler

On the basis of the produced mental - verbal and structural models the flowchart of the ship steam boiler in POWERSIM simulation language is produced, according to [14].

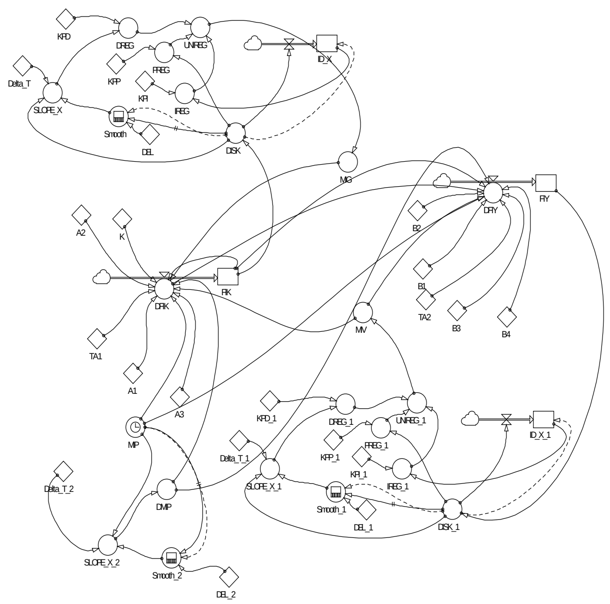

Fig. 5. Global flowchart of the ship steam boiler with the built-in PID governors

3. Investigating performance dynamics of the ship steam boiler in load conditions

After system dynamics qualitative and quantitative simulation models have been produced, in one of the simulation packages, most frequently DYNAMO [15] or POWERSIM [14], all possible operating modes of the system will be simulated in a laboratory.

After the engineer, designer or a student have conducted a sufficient number of experiments, or scenarios, and an insight has been obtained about the performance dynamics of the system using the method of heuristic optimisation, optimisation of any parameters in the system may be performed, provided that the model is valid.

In the presented scenario the simulation model of the ship steam boiler for the steam pressure and the water level with two built-in PID governors will be presented, [16], [17] and [18].

1. Consumption of the steam is determined by the impulse function of 50-sec duration, which means from 200 – 250 sec, and MIP = 0, FIK = 0, FIY = 0.9999 at the initial TIME = 0.
2. Fuel supply MIG is determined as an outlet of PID-governor, at which inlet there is the discrepancy of the steam pressure (1-FIK) and correspondingly, the water supply MIV is outlet of the other PID-governor, to which the inlet is discrepancy (1- FIY).
3. Other parameters of the ship steam boiler equal nominal values.

Graphic results of the simulation:

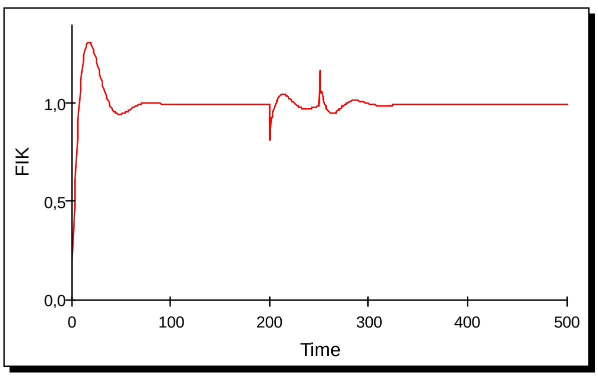

Fig. 6. Relative state of the steam pressure in the steam boiler

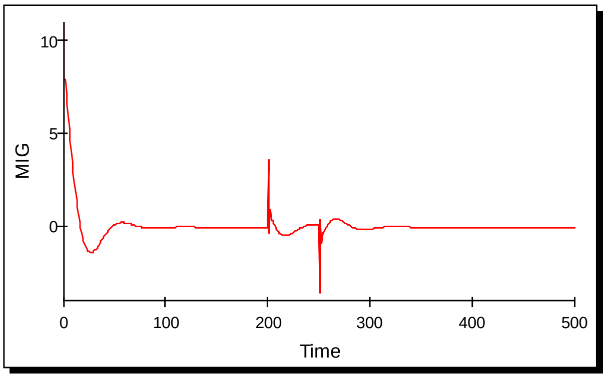

Fig. 7. Relative change of the position of the fuel valve

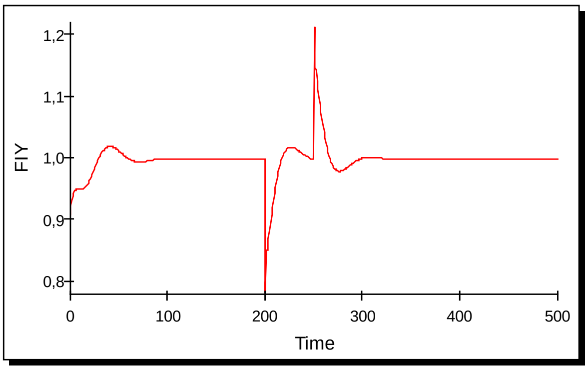

Fig. 8. Relative state of the water level in the steam boiler

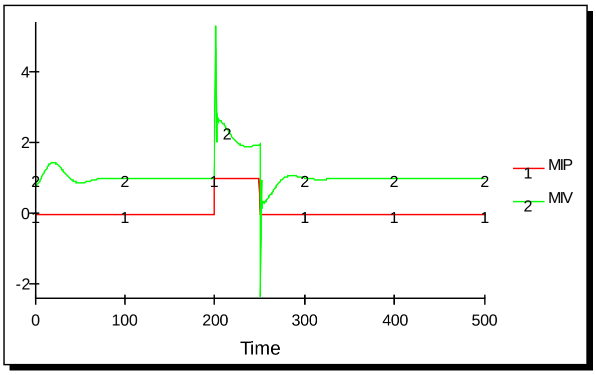

Fig. 9. Relative change of the position of the feed water valve and relative change of the position of the steam discharge valve

From the results of the simulation it may be observed that the model shows real performance dynamics and that by applying PID governors and adequate values of coefficients better levelling and attenuation of the transition occurrence of the variables FIK and FIY will be achieved.

4. Conclusion

System dynamics is a scientific method which allows simulation of the most complex systems. The method used in the presented example demonstrates a high quality of simulations of complex dynamic systems, and provides an opportunity to all interested students or engineers to apply the same method for modelling, optimising and simulating any scenario of the existing elements.

Furthermore, the users of this method of simulating continuous models in digital computers have an opportunity to acquire new information in dynamic systems performance. The method is also important because it does not only refer to computer modelling, but also clearly determines mental, structural and mathematical modelling of the elements of the system.

This paper's contribution is as follows:

1. New insights have been made into performance dynamics of a complex ship boiler system. All relevant causal connections have been defined as well as relevant feedback loops dominating within a ship steam boiler,
2. The design of the dynamic simulation model of a ship steam boiler enables diagnosis, condition forecasting, and higher quality of decision making, aiming at the safe managing of the operation of the ship as a whole,
3. In the process of education of present and future university marine and electro technical engineers in the field of simulation modelling of complex organizational, natural, and technical systems,
4. Enables students, technicians and engineers to "feel" the performance dynamics of the ship steam boiler as a whole at any moment,
5. Enables designers of new ship propulsion systems and processes to get necessary information in the stage of designing by using computer in applying the systematically dynamic scientific method of simulation modelling, and to avoid waiting for the results of experimental testing,
6. Forming basis for further scientific research of the performance dynamics of ship propulsion systems as a whole, and of ship handling systems in view of the long-term development project of the "intelligent" ship handling.

In this paper we have presented an efficient application of the system-dynamic methodology of simulation modelling while investigating the

performance dynamics of technical systems with non-linear characteristics, aiming at a more thorough research of performance during transient phenomena occurring when working conditions and exploitation loads are changed.
This paper deals with the ship steam boiler, i.e. we have made qualitative and quantitative simulation models based on the mathematical model which is partly taken from [2] (pages 26-31). Eventually the model has been shown with a set of differential equations, which indeed makes it one of exceptionally complex technical systems with dominating set of relevant causal connections and feedback loops that we have defined. The simulation has been carried out with regard to the performance dynamics of the observed systems.

References

[1] Forrester, Jay W., *Principles of Systems*, MIT Press, Cambridge Massachusetts,USA, 1973.

[2] Nalepin,R.A.,Demeenko, O.P., *Automation of energetic system*, Leningrad,Sudostroennie, 1975.

[3] Šretner, J., *Marine steam boilers*, Sveučilište u Zagrebu, Zagreb, 1975.

[4] Šneller, S., *Ship propulsion I – steam generators*, Sveučilište u Zagrebu, Fakultet strojarstva, Zagreb, 1996.

[5] Prelec, Z., *Ship steam generators*, Školska knjiga Zagreb, Zagreb, 1990.

[6] Milton, J.H., *Marine Steam Boilers*, Butterworths, London, 1985.

[7] Isakov, L.I., Kutljin, L.I., *Complex automation of Diesel and gas turbine system*, Leningrad, Sudostreonnie, 1984.

[8] Munitic, A., *Computer Simulation with Help of System Dynamics*, Croatia, BIS Split, 1989.

[9] Gradišar, D., Mušič, G., *Production-process modelling based on production- management data:a Petri net approach*, International Journal of Computer Intergrated Manufacturing, Vol. 20, No. 8, pp. 794-810, 2007.

[10] Dvornik, J., Dvornik, S., *Simulation modelling and heuristic optimization of the ship steam boiler*, The 26th IASTED International Conference on Modelling, Identification, and Control, MIC 2007, Innsbruck, Austria, pp. 105 – 108, 2007.

[11] Dvornik, J., Milic, L., Dvornik, S., *Simulation of dynamics working conditions of the ship steam boiler,* International Scientific Conference on Production Engineering, Lumbarda, Korcula, Croatia, pp.137-143, 2006.

[12] Dvornik, J., Dvornik, S., Tireli, E., *System dynamics simulation model of the ship steam boiler, 11th World Multiconference on Systemics, Cybernetics and Informatics,* WMSCI 2007, Orlando,USA, , pp. 25-29, 2007.

[13] Dvornik, S., Kulenovic, Z., Dvornik, J., *Qualitative simulation model of the ship steam boiler*, 12th World Multiconference on Systemics, Cybernetics and Informatics, WMSCI 2008, Orlando, USA, pp. 100 – 105, 2008.

[14] Byrknes, A. H., *Run-Time User's Guide and Reference Manual,* Powersim 2.5, Powersim Corporation, Powersim AS, 12007 Sunrise Valley Drive, Reston Virginia 22091 USA

[15] Richardson, George P. and Aleksander L., *Introduction to System Dynamics Modelling with Dynamo*, MIT Press, Cambridge, Massachusetts, USA, 1981.

[16] Suprun, G.F., Dynamics of electro-energetic system, Leningrad, Sudostroenie, 1972

[17] Hind, A., Automation in merchant ships, London, 1968.

[18] Fowler, A., *Microcomputer-based Simulation on Marine Propulsion Systems*, Transaction JmarE, VOL 100, pp.13-29, 1988.

[19] Rend, C. K., *Practical Marine Engineering*, Prentice Hall Inc., New Jersey, 1965.

[20] Yaverbaum, L. H., *Energy Saving by Increasing Boiler Eficiency*, Noyes Data Corporation, New Jersey, 1979.

[21] Dvornik J., Tireli E., Dvornik S., *Analysis of the Permormance of the Ship Steam Boiler using Simulation*, Thermal Science - scientific journal, Society of Thermal Engineers of Serbia, Institute for Nuclear Sciences VINČA, POB 522, 11001 Belgrade, Serbia, Vol. 13, No. 4., pp 11-20, 2009.

[22] Tireli E., Dvornik J., Dvornik S., *Application of Simulation Modelling to the Ship Steam Boiler System*, The 7TH International Workshop on Modeling & Applied Simulation, MAS 2008, Campora S. Giovanni/Amantea (CS), Italy, September 17 – 19, pp. 198 – 203, 2008.