The use of simulation models in education: the affordable engineer

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SYNOPSIS

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INTRODUCTION

One, if not *the*, main asset of any navy is its personnel. The Mechanical Engineering Officer is a Marine Engineer who is expected to have both theoretical and practical knowledge, paired with the ability to quickly assess new, unexpected and often threatening situations and take appropriate actions. Educating and training Marine Engineers is very expensive; a lot of effort and time is needed to provide them with enough knowledge and experience to develop a thorough understanding of complex systems. The Marine Engineer needs to build up a mental picture of the functioning of a system, often just from drawings, while including all possible failures and aspects of off-design and dynamic behaviour. Pairing the theoretical knowledge from lectures with the practical insight in complex system interactions is a major challenge facing the educators.

Experimental facilities are expensive to run, and offer an indispensible but limited environment for building the required knowledge. Simulation models, if based on physics (i.e. first principle models), offer an excellent opportunity to let students become aware of the complexity of the interaction occurring in a real system. This however does imply that the model should include all major dynamics, but more importantly also all non-linearities such as limiters, safeties and switches/valves. Especially those non-linear elements confront the students' theoretical knowledge with reality, as "unreal" processes occur from a theoretical perspective.

Author's Biographies

Douwe Stapersma graduated in 1973 as a mechanical engineer at Delft University of Technology in the field of gas turbines and then joined Nevesbu - the Dutch design bureau for naval ships - where he was involved in the design and engineering of the machinery installation of the Standard frigate. After that he co-ordinated the integration of the automatic propulsion control system for a class of export corvettes. From 1980 onward he was responsible for the design and engineering of the machinery installation of the Walrus class submarines and in particular the machinery automation. After that he was in charge of the design of the Moray class submarines in a joint project organisation with RDM. Nowadays the author is professor of Naval Engineering at the Royal Netherlands Naval College and lectures Marine Diesel Engines at Delft University of Technology. His main research topics are Fuels & Emissions and Dynamics of complex Marine Systems.

Hugo Grimmelius holds the position of assistant professor Marine Engineering at the Delft University of Technology since 1997. He obtained a bachelor's degree in Marine Engineering in 1986, and sailed on merchant ships as engineer for a short period. In 1992, he graduated from Delft University of Technology in Marine Engineering on a thesis on condition monitoring. This research was further developed to a PhD thesis (2005). He has published over 40 papers on a wide variety of Marine Engineering related subjects. His main research topics are the dynamic behaviour of complex systems and maintenance engineering.

Peter de Vos holds the position of researcher in Marine Engineering at the Delft University of Technology since 2008. He obtained a bachelor's degree in Marine Engineering in 2006, and continued in a MSc study until in 2008, he graduated from Delft University of Technology in Marine Engineering on a thesis on dynamic simulation of a reformer for a fuel cell.

In this paper the authors will discuss how such a simulation model should be developed using a modular, parameterised and first principle based approach. Examples will be given how these models can be used to teach complex interactions in various fields, including diesel engines, HVAC equipment and ship propulsion.

WHY SIMULATE?

At the previous INEC conference the authors argued that there are at least two types of questions that can be answered using simulation, [1]:

A It is required to get an *accurate numerical answer* to the question how certain variables behave in reality before the component or system is actually operating or before it has been built at all. In this case one wants to *calculate*.

B One wishes to gain a *global insight* of how input variables or internal parameters affect the output variables. Now one wishes to *comprehend*.

Obviously when looking into the potential of the use of simulation in education we are in the B category. But what is there to comprehend and how was it done before simulation became part of the tools available to education? The competence of a marine engineer (whether on board or in the design office) is to comprehend how the ship's operation translates into functions and how these functions are realised in shipboard systems. But these systems are multilayered in the sense that any system consists of subsystems and these will consist of components. Complexity arises because:

- There are parameters and variables on all levels, which means that changes in behaviour and causes for disturbances may enter at any level
- These layers interact not only at equal level but also across levels.

What the authors mean by a "mental picture" is that a marine engineer must be aware of these layers, must know what parameters and variables are important and where they act on the system and finally how they interact at other places in the system. It is difficult to prove that such a mental picture is a necessity but the following argument is held by the authors. In this age of automation, the main role of the marine engineer on board is calamity fighting. Whether even this can be automated and even warships could be unmanned is a matter of debate in this conference. But for the moment training engineers for calamities can and must be done in simulators or on board and constitutes of procedure training [2]. It is assumed that all foresee-able calamities can be transformed into procedures and these can be drilled. But how to manage the unexpected? The authors believe that for these eventualities marine engineers should have a good basic knowledge of physics and technology, which always has been part of their education, but also have this "mental picture" of the systems on board. Although systems engineering is now part of the curriculum for at least 20 years and textbooks are available for that [3], this ultimately may not be sufficient and simulation tools can provide training to obtain the required "mental picture". A marine engineer educated this way may prove to act adequately even when called upon in a completely new and unexpected situation.

For the academically trained marine engineer in a design environment in an on-shore job having a deep insight in the complexity of systems is beyond doubt and simulation tools may help him when it comes to making decisions to the control and monitoring of systems and for verification during all design stages. Also another risk for "design office engineers" i.e. becoming a clerk without any touch and feel with the actual operation of systems could be mended by the use of realistic first principle simulation tools.

WHAT CAN BE SIMULATED?

At component level education would classically consist of

- Teaching the theory of the component in class
- Illustrating the theory in practice on such a component in a laboratory

For a component one could think of a pump, heat exchanger, compressor, diesel engine, gas turbine etc. in the sense that for these a test facility is feasible, although nowadays not always affordable. But there is a more fundamental problem: in particular a diesel engine and a gas turbine already must be viewed as complex systems in itself, consisting of components at a lower level, e.g. a modern diesel engine is a combination of a compressor, heat exchanger, cylinder process and turbine while even the simple cycle gas turbine is a complex entity consisting of compressors, combustion chambers and turbines. A simulation model of these pieces of machinery could uncover the complexity and train the student also at this component level to compose a mental picture. A simulation model of a diesel engine is available at

NLDA/TUDelft [4] and the complex interaction with a turbocharger was the subject of the already mentioned paper [1]. A gas turbine simulation model based on the same principles is being developed.

But one could go even deeper down to the level where there are no subcomponents but only empirical physical models and first principles, the latter often being mass, momentum and energy conservation., i.e. generalized volume and pipe elements. Examples are:

- modelling an axial compressor from elemental stages connected by volume elements, in which the interaction of the enthalpy and flow coefficients at stage level and their effect on overall pressure ratio, flow and efficiency (i.e. the compressor map) could be studied in depth.
- modelling a heat exchanger by elements comprising the heat exchange through the three resistances (convective heat exchange near the wall of the two fluids and heat conduction in the wall) and heat accumulation (mainly in the wall but also in the fluids). The stacking together of elements gives the temperature distribution of the two fluids within the heat exchanger.
- the cylinder process in the diesel engine could be viewed as a volume element where the the first principles of thermodynamics interact such as to produce the overall time evolution of temperature, pressure and gas composition within the cylinder. At NLDA/TUDelft a cylinder process model covering these issues is available [5].

Of course combining these sub-elements at a higher level to really complex systems is the ultimate subject of marine engineering. A (waste heat) steam installation for instance is a combination of volumes, pipe elements, heat exchangers and pumps and a model covering such an installation was recently developed [6]. Another example is a reformer plant for a fuel cell, a model of which was presented at WMTC 2002 [7]. The latter exemplifies the fact that marine engineering is not about mechanical engineering only: in particular electrical systems play an important role in onboard systems. Models for AC and DC machines [8] and batteries [9] may therefore not be absent in a library of models that has the ambition to embrace all marine engineering systems.

On the highest level these systems can be combined to the complete propulsion system of a ship that can be connected to a ship manoeuvring system [10]. Alternatively it can be extended to simulate the complete energy generating & conversion system on board the ship. Also the auxiliary systems, such as cooling systems can be connected to these. An auxiliary system that is particularly important for warships is the HVAC system, the complexity of which is high, due to the interaction of the air circuit, chilled water system, chiller (freon) system and ultimately the sea cooling water system [11].

At this level, systems cannot be accommodated in a laboratory at least not on an affordable scale. Of course models as described are used in machinery trainers but then the purpose is procedure training for which the requirements are different and more pragmatic models will suffice. If however complexity of systems and obtaining a mental picture thereof is an educational goal itself, the requirements for modelling may be different and also one must think how to use these models in an educational setting.

COMPLEXITY AND AUTOMATION

Complexity was already defined as being determined at least by the presence of (a) multiple layers, (b) many parameters and variables and (c) interaction *at* all levels and *between* all levels. But there is more to say about it. First of all one should differentiate between the complexity of the plant itself and the (added) complexity of the Control & Monitoring layer that is put between the operator and the plant, refer to Figure 1. Then this extra layer in itself can be complex as illustrated in Figure 2.

What is vitally important for building up a mental picture of the complete system is to have a proper knowledge of the routing of the in- and output signals. One can easily confuse students by asking what the input of a propulsion system is. Many will answer: shaft speed, but strictly speaking this is an output (it is even a state variable of the system) while fuel setting really is the input of the core propulsion system. Of course shaft speed *setting* is an input in case of the controlled system, i.e. including a speed governor. In this case the mental picture of the student lacks two notions: the difference between *controlled* variables and *controlling* variables, refer to [12] and the failure to realise what the system boundary of the plant is and how that boundary changes when automation is added. Also the fact that automatic systems themselves require manual input commands, often however of a higher order such as a single lever command for a combined shaft speed and pitch setting, is part of a mental picture that for most students is not trivial at all. Moreover these higher order control systems, e.g. a power management system can be physically separated from a lower grade control system that actually controls the system. This becomes important if certain parts of a system fail but others remain intact and functioning. Also vital to the operator, in particular in calamity situations, is the notion that there may be autonomous systems as well, see Figure 2.

On the monitoring side it is essential to know when and where use is made of independent sensors and where and what these sensors exactly measure. A sensor displaying fuel rack of the diesel engine could physically be located on the rack itself, measuring distance or rotation, or be the output of an electrical signal to the actuator. But is often cheaper to take the output of the electronic governor (i.e. demanded fuel rack) but then it could easily be either before or after a step/ramp converter. Also it would be a question whether the signal is taken before or after applying limits caused by actual speed and/or receiver pressure. The interpretation of the signal in all these cases is different of course. This example also shows that also on the control side (since fuel rack, although monitored, is an input as well) it is important to understand when and where inputs are limited and where the rate of change of input signals are controlled by for instance step/ramp converters.

All this knowledge will be necessary in a situation where parts of the system have failed. Then first and foremost it must be assessed what information is still valid and what parts of the installation still might function. Also it must be quickly decided what means of control are still available and whether they are different from the normal means of control. This not only is important for the marine engineer in charge on board but also for the marine engineer in a design office: the most important aspect of designing automation systems is behaviour after failure.

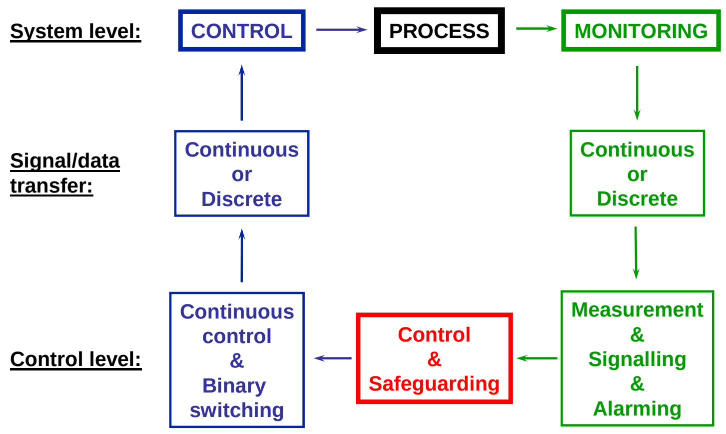


Figure 1 Control & Monitoring: terminology

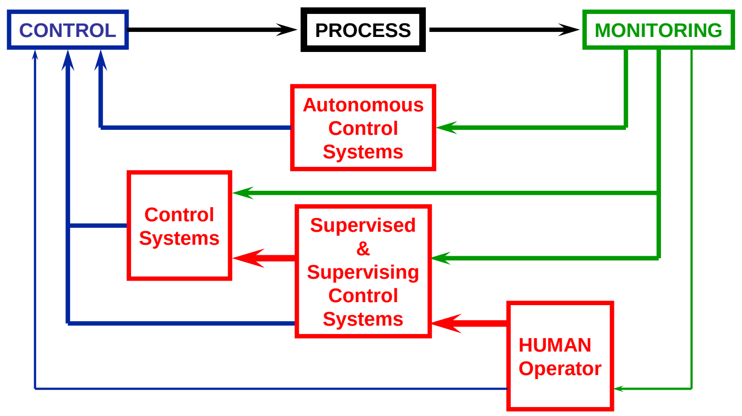


Figure 2 Control & Monitoring: layers and levels

SIMULATION MODELS SUITABLE FOR EDUCATION

From the above some conclusions can be drawn for specific requirements of simulation models that are suitable for the educational goal of understanding system complexity (i.e. not training system procedures: that is done in simulators):

- The actual layered structure of the systems must be reflected in the hierarchy of systems and subsystems in the model and easily be understood by students.
- In particular the plant and the control systems must be clearly separated in the model. Also the model and the experiment must be separated. In fact the models of the plant and often also of the control system are provided to the student (building models is another educational goal and should be taught in another subject) while designing the experiment in this case is the student's task. For the student, understanding complexity is essentially to invent experiments that will cleverly make a distinction between influences (inputs and parameters) and then observe the differences in behaviour.
- On the monitoring side simulation models are ideal in the sense that sensors can be located anywhere even at places where it would be impossible in practice. Students however must be able to easily pick sensor locations and decide where to look when they do not understand the system behaviour. This will later help them understand system behaviour even if the sensors are not available.
- Although the models need not to be very precise they should be intuitively right. In aircraft simulators the term "fidelity" is used for this aspect, but training in this respect has other (and often more severe) requirements than education. For educational goals however simulation models are required to be in essence according to first principles. In [1] it was explained that for practical reasons at a certain level one always has to return to empirical models. Exactly at what level one has to rely on empirical models depends on the overall level of the model. For instance when trying to understand the complexity of a propulsion system, one could decide to use an empirical model for the prime mover. When that prime mover is a gas turbine one could however also decide to use a first principle model based on the power balance of the rotors that are present (e.g. gas generator and output shaft) but use empirical maps for the characteristics of the compressors and turbine. But alternatively one could adopt a compressor and turbine model at least based on Euler's theorem, with some empirical assumption for the irreversible losses. Normally for the combustion chamber the static version of the mass and energy balance will suffice to give acceptable reality to the model but a refined model would have the dynamic form of mass and energy balance as available in the volume element developed at NLDA/TUDelft for use in this type of chemical/thermodynamic systems
- In [1] it was argued that models should be parameterised and in first principle models lead to *physical parameter*s and *model parameters*. Both must intuitively be understood by students and easily be changed. In a MATLAB/Simulink environment this has led us to strictly forbid hiding parameters within the Simulink model: rather they should be transparently accessible in a MATLAB file. Students should be invited to play with these parameters since playing is perhaps the best way of learning.
- All important is the modelling of all sorts of limiters. The earlier given example of the fuel rack shows that the maximum fuel rack (and thus torque output of the diesel engine) may be limited in the governor, be restricted by a step/ramp converter in the control system and finally by the dynamics of the fuel rack itself (it has a finite mass) and the mechanical fuel stop. Ultimately the actual fuel injected to the engine is further restricted by the maximum capacity and the leak of the fuel injection pump or common rail system. Equally the propeller pitch and rate of pitch change in case of a CPP could be restricted by algorithms in the control system, by the dynamics of the hydraulic control valve or by the pump capacity in relation to the hub size. It is important that a student is able to understand which of these limits in a particular situation will determine the ultimate behaviour.

CASES

In order to illustrate how simulation tools can help teaching marine engineering at academic level two cases will be presented. First a waste heat boiler system in the exhaust of a diesel engine as an example of a complex auxiliary system, the operation of which is not easy to understand and for which the way of controlling is critical to the systems safety. Finally a propulsion system, not a classical with diesel engines or gas turbines as prime movers but one with a fuel cell as energy generator and battery as a energy storage device. This example will show the benefit of simulation tools when it comes to discussing future systems for which a real plant even is not available.

Case 1: Understanding component interaction in a waste heat recovery steam system

Systems can be complicated because of the character of the components, like demonstrated in the first case. Another kind of complexity results from the interaction between in itself simple components. Especially when this interaction takes on the form of a closed loop, students often find it difficult to understand, let alone predict, the resulting behaviour. An example of such a system is a steam plant. In basic thermodynamics courses the Rankine cycle is always taught, yet when faced with the 'real thing' students fail to operationalise this theoretical knowledge to find solutions, either when facing a design challenge or when facing operational issues.

The use of a dynamic simulation model in this case enables the student:

- To experience the (often long) time delays in the system.
- Change the control settings and control strategies.
- Interactively experience the interconnectivity between the components in the cycle.

The dynamic simulation model is based on Figure 3, which shows a simplified layout of a WHR-system. The water cycle 'starts' at the feed water pump (1). Water is pumped from the feed water tank (12) through the pre-heater (2) and economizer (3) to the steam drum (4). From the steam drum water is pumped (5) through the evaporator (6) back to the steam drum. Here the vapour is separated in steam and water. The steam flows through the super heater (7), inlet valve (8) and steam turbine (9) to the condenser (10). This water is pumped by the vacuum pump (11) to the feed water tank.

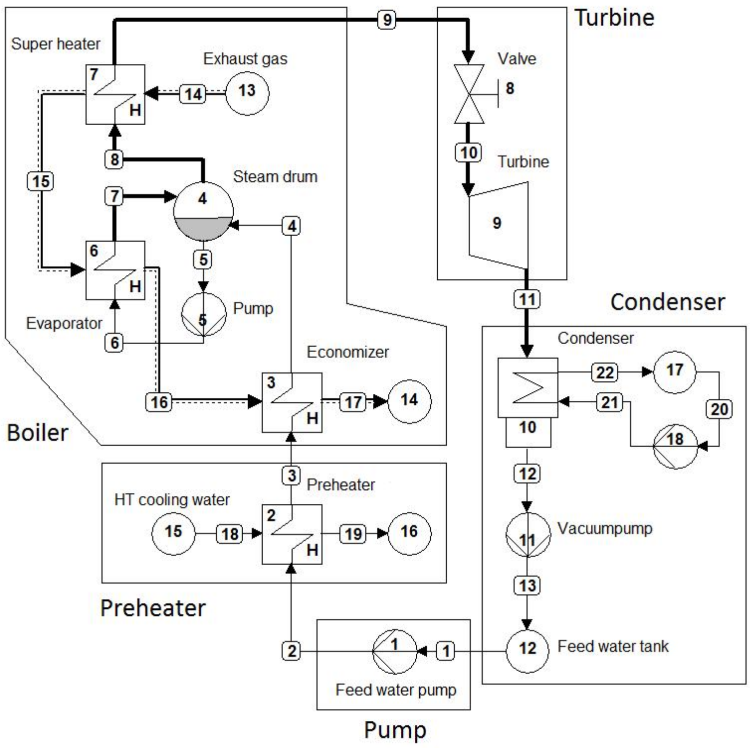


Figure 3 Simplified WHR-system layout

Assumed is that the WHR system will remain operational as long as steam is produced. The limits of the steam turbine are not included. In this case one of the critical boundary conditions of the boiler is the exhaust gas temperature after of the boiler. The temperature should stay above the condensation temperature of sulphur oxides.

The simulation model is build up from 'vessel' and 'resistor' elements to ensure causal modelling, Figure 4. The boiler and pre-heater model together give the high pressure (p_{blr}) in the system, the condenser model gives the low pressure (p_{cond}). The feed water pump model and the turbine (including the inlet valve) model give the mass flows. (The temperature is determined in all models and its calculation is sequential, i.e. follows the mass flow through the system.) This structuring of dynamic systems helps to understand the interactions that dominate the system behaviour and hence the control options.

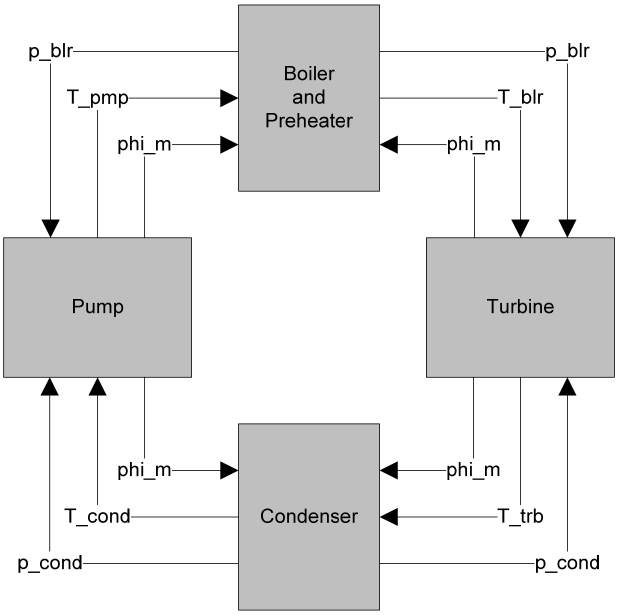


Figure 4 WHR model causal representation

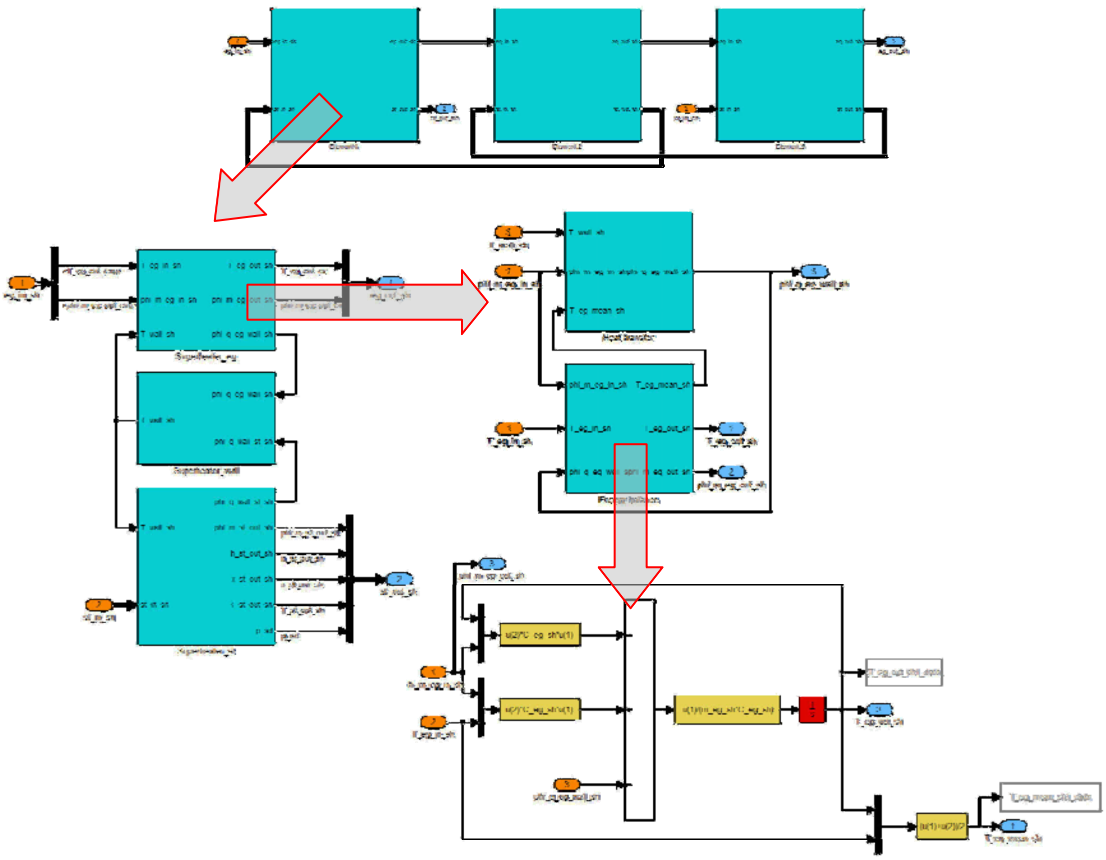


Figure 5 Example of model structure: the super heater model consist of three elements (top) each element has a exhaust gas (eg) side, a wall and a steam (st) side and a wall (middle left), the exhaust gas side comprises of a heat transfer calculation and a energy balance, the energy balance is a straightforward simple implementation of the first law of thermodynamics, resulting in the average temperature.

In Figure 4 the high level models as shown consist of various sub-models:

- The ‘Boiler and pre-heater’ comprises of four heat exchangers:
  1. A pre-heater to heat up the feed water and reduce the risk of cold spots in the boiler.
  2. An economizer to heat up the feed water and utilize the last energy in the exhaust gasses.
  3. A ‘wet’ evaporator to evaporate the water. The pump (# 6 in Figure 3) always supplies more water to the evaporator then will evaporate.
  4. A super heater to superheat the steam before the turbine.

  These heat exchangers are connected to the steam drum were the pressure is determined.
- The ‘Turbine’ consists of the control valve, the turbine (which is modelled with a constant isentropic efficiency) and a PID controller for the valve.
- The ‘Condenser’ model contains a two phase heat exchanger, a cooling water pump and a PID controller for this pump.
- The ‘Pump’ model contains the feed water pump and a PID controller for this pump.

The model is build such that basic structures and underlying equations are easily recognised when students inspect the model, as illustrated in Figure 5. The whole model is parameterized and data from a basic design exercise are sufficient to create a working system. All properties of water/steam are based on ‘FluidProp’ [13], exhaust gas is treated as a perfect gas.

The first result from working with the model is a better understanding of the static behaviour and the associated characteristics. The model will generate the Q-T diagram for various loading conditions, which helps the student to understand the change in behaviour and illustrate the use of Q-T diagrams in general. In the left Q-T diagram the exhaust gas temperature ends at the critical level of 160 ^{o}C. On the right, it is clear that at lower loads the economiser takes to much heat, and the exhaust gas temperature drops to an unacceptable level of 150 ^{o}C.]

The next step is analysing the dynamic behaviour of this system under suddenly changing loads. Figure 7 shows the response of the system to a sudden reduction of exhaust gas flow. The heat flows from the exhaust gas to the wall and from the wall to the steam are shown. To explain this behaviour, the student will have to thoroughly understand the physics and the interactions:

> First (1) the heat flow from the exhaust gas reduces immediately, because the convective heat transfer is a direct function of the mass flow. Then (2) the heat flow to the steam is larger for a while due to the reaction time of system and the steam flow controller. The tube wall cools down, which causes the heat flow from the exhaust gas to rise again! As a result (3) the heat flow to the steam becomes smaller than the heat flow extracted from the exhaust gas, so tube wall temperature starts to rise again. This reduces the heat flow from the exhaust gas. After about 300 s the controller has found a new mass balance (4), so the heat transfer coefficient on the steam side is more or less constant again. In the mean while the tube wall temperature continues to rise (5) due to the higher heat flow from the exhaust gas. This reduces the heat flow from the exhaust gas and increases the heat flow to the steam. Finally, after 1500 s (25 minutes!) the heat flows are in equilibrium again.

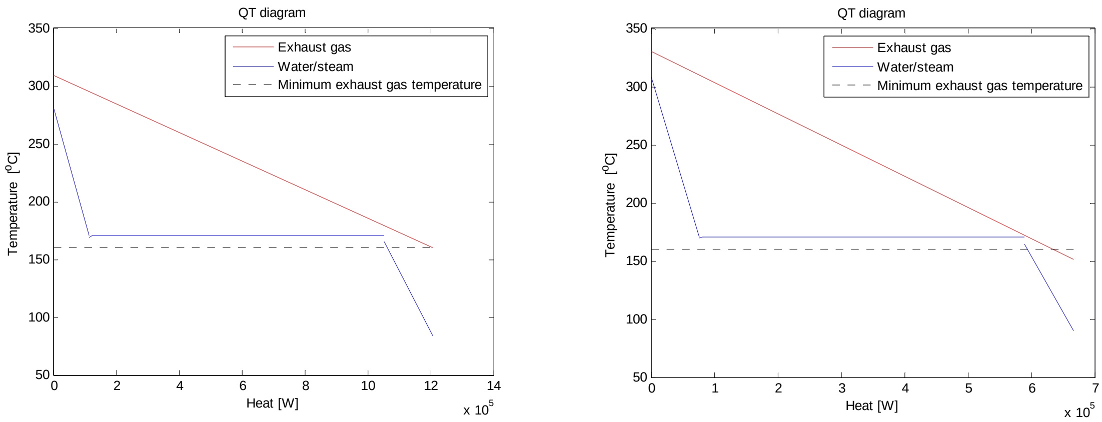


Figure 6 Q-T diagram for design condition (left) and reduced load (right). The

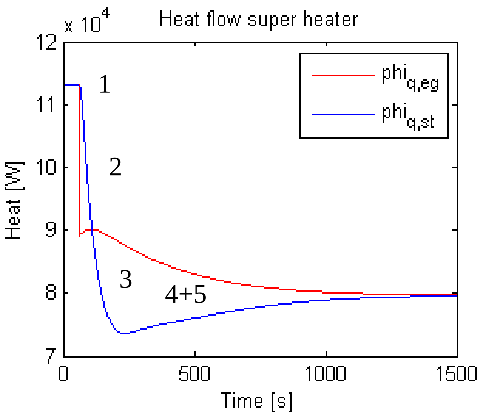
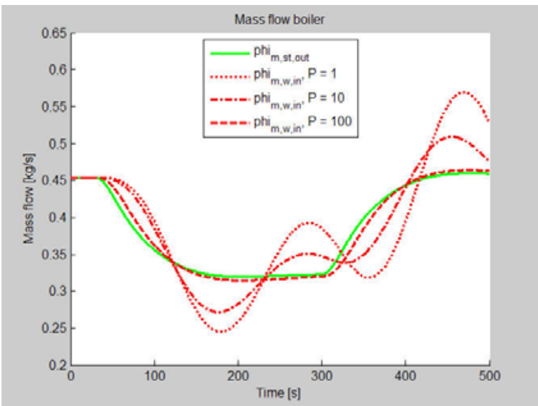


Figure 7: Heat flow in super heater after exhaust gas mass flow step

The model also enables the evaluation of controller settings and strategies. In the model as presented here the three PID controllers each control one aspect of the system: the PID controller for the steam flow controls the high pressure, the PID controller for the feed water pump controls the water level in the steam drum and the PID controller for the cooling water pump controls the low pressure. The model makes it possible to change the settings but also to change the controlled variables in the system or the control regime,

Figure 8 illustrates the effect of changing the proportional gain for the feed water pump controller. Though the results are not spectacular it does offer the students a good opportunity to test their understanding: at low gains the response is slow, at high gains.

A way to improve the part load behaviour as shown in Figure 6 is by adjusting the steam pressure dynamically. This can be evaluated within the model by for instance an additional feed forward control on the pressure set point. The resulting behaviour is shown in Figure 8 on the right.



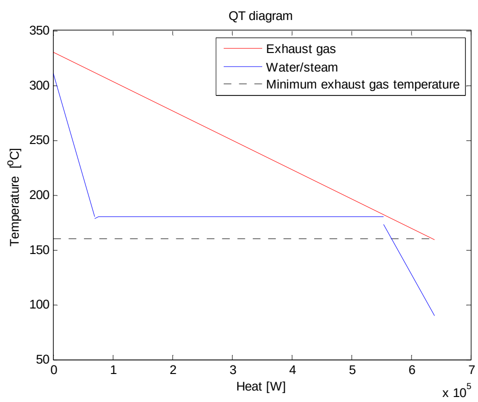


Figure 8 Feed water mass for different proportional gain settings (left) and Q-T diagram for reduced load and increased pressure (right)

Case 2: Understanding component interactions and control of hybrid fuel cell – battery system:

So far complex systems have been discussed that exist in present ships. However, marine engineering students, being the future marine engineers, are interested in possible future marine engineering systems as well. There are always good reasons to hold on to current systems and technologies, such as system familiarity, operational experience, prediction of maintenance etc. But the present debate on global climate change induces great environmental awareness which may lead to radical changes in marine systems in order to decrease environmental impact and thereby complying with future legislation. This trend is noticed by marine engineering students as well and it makes them eager to learn about other technologies, like fuel cells and hybrid electric systems as applied in e.g. the Toyota Prius, in particular since these systems in naval ships also decrease the noise signature. This eagerness of students can be employed to teach them about component interactions of future systems, which is at the core of marine engineering.

During an exploratory research a model simulating the dynamic behaviour of a hybrid FC (fuel cell) system for application in inland ships was developed at the TU Delft, [14]. This model can also be applied in education in order to make the students obtain the following learning goals (amongst others):

- Describe and explain a typical FC voltage-current characteristic and the factors that shape it
- Describe and explain typical battery voltage-current characteristics
- Understand why a dynamic model is needed when modelling hybrid power systems (how else could one account for energy accumulation in the battery)
- Understand the greater difficulty and increased importance of control systems in hybrid systems.

The first two goals are easily achieved by placing the component models (fuel cell and battery), or rather a characteristic based on some basic theory, in a test environment and ask the students to create the characteristics using the model; this requires them to understand the component model and therefore the theory that is in it. Understanding the characteristics of the components is necessary to achieve the third and fourth learning goal, which are true marine engineering challenges, because mastering these is only possible through understanding the complex interactions between the components.

Fuel cell characteristic:

Basic models of fuel cells can be found in typical text books, like [15]. Essentially a FC characteristic is built up from the theoretical reversible voltage minus chemical activation losses minus ohmic losses minus chemical concentration losses, see Figure 9. The basic theory model from [16] was implemented in Matlab and Simulink. The results of this model are shown in Figure 9 as well. Students can “play” with the parameters of this model in a test environment and find out how e.g. the activation losses affect the FC characteristic. When they understand the characteristic they are ready to move on to the next phase: interactions of components and control of the complete, hybrid system.

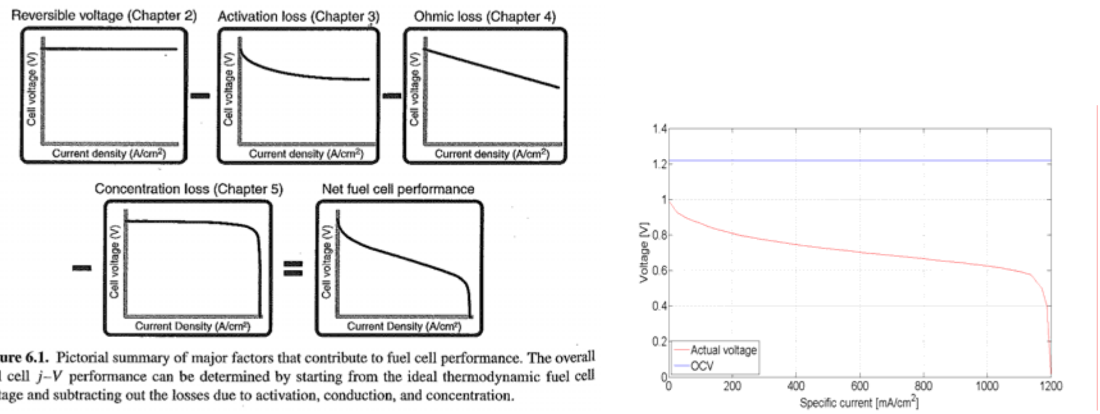


Figure 9 Build-up of FC characteristic, ref [16] (left) and FC characteristic from model (right).

Control system:

The input of a hybrid FC system model is the power demand of an inland ship. This power demand is created from torque and speed measurements on the propulsion shafts of an inland tanker sailing from Rotterdam harbour to Marl in Germany, but could of course be based on any other desired operational profile. This can be used to demonstrate to students for which types of operational profiles hybrid systems are best suited in terms of fuel savings: ships that run their engines at low power for long periods of time.

The top layer of the model is shown in Figure 10; one can recognize the input on the left and the system component models on the right; of course all models (blocks) are multi-layered and contain a certain number of subsystems. When the students are handed the model they can simulate the journey from Rotterdam to Marl. They can also choose two control algorithms: one activates extra FC stacks, which are connected in parallel, when the already operating stacks are at their maximum load, in much the same way as current diesel generator sets are used on board. The other control algorithm makes all FC stacks operate no matter their load. This last control algorithm saves a lot of fuel (~20%) on the journey from Rotterdam to Marl. This is caused by the high efficiency of fuel cells at low load with respect to their nominal power, which is very specific for fuel cells of course and totally different from diesel engines, which operate most efficiently at high loads with respect to their nominal power.

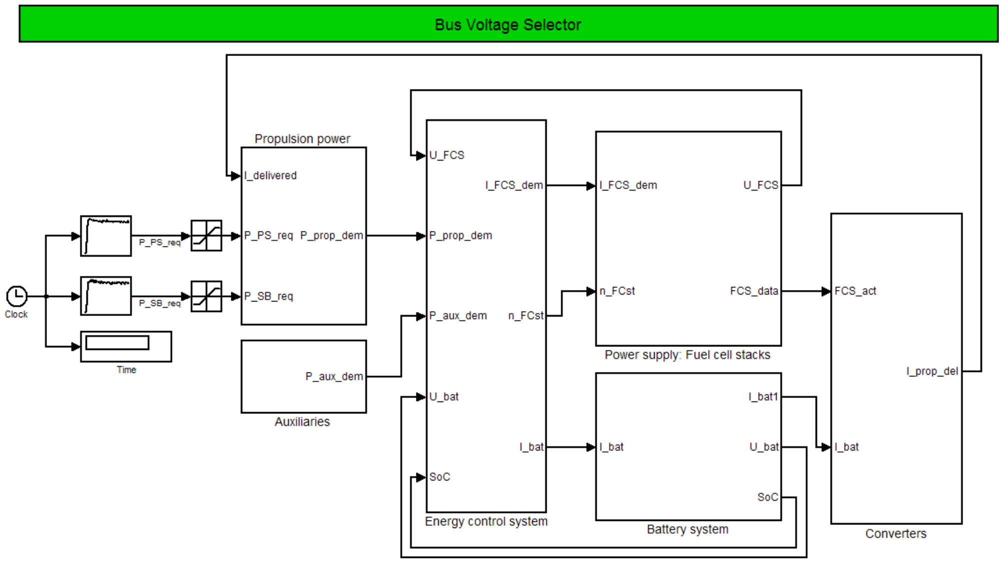


Figure 10 Top layer of hybrid FC system

These are the results of the simulations with both control algorithms (output of the model):

- Total fuel consumed during journey: 922.74 kg H2. This is equivalent to: 3.086 ton diesel
- Total fuel consumed during journey: 758.90 kg H2. This is equivalent to: 2.538 ton diesel

These results can also be seen in Figure 11, where the area below the lines represents total fuel consumption.

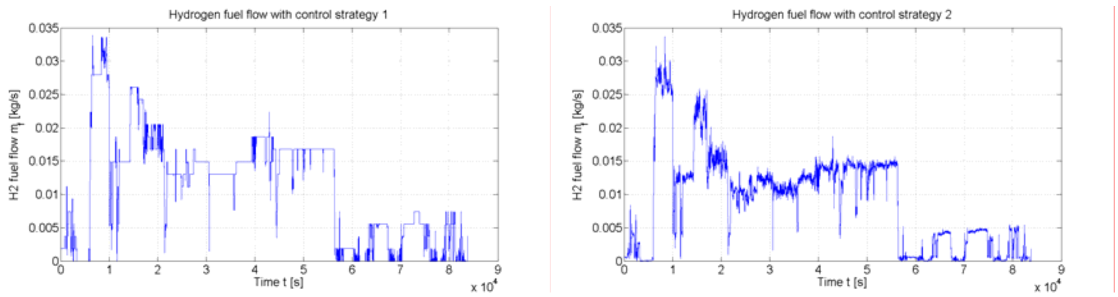


Figure 11 Hydrogen fuel flow with more energy efficient control strategy on the right

When a student is faced with these results and is asked the question what causes this difference, he/she needs to look into the model and both control algorithms, and only when he/she understands the interactions in the system and the dependency of the results on the operational profile will he/she get the right answer. All kinds of variations with fuel cell type, battery type and battery control can also be implemented easily with the described model. This creates a lot of opportunities for the students either to pick up specific knowledge about these kinds of hybrid systems or to test their insight into component interaction in a system that is not typical for present marine engineering systems.

CONCLUSIONS

Simulation can and must be used in education. Simulation models for education however have other requirements than models for developing systems in industry or even models used in simulation trainers. For education the most important features are transparency of the models, and visibility of first principles. Also adaptability by manipulating well understood parameters is a prerequisite. Last but not least the output of the model should be easily accessible and correspond with knowledge level of the students.

In the cases that were presented it was demonstrated that the learning goals that can be supported by simulation are:

- Deeper understanding of basic physical principles by making them "operational".
- Understanding of the interaction of simple phenomena at low level and the resulting effects at higher levels (in fact: complexity)
- Learning where to look in case of faulty behaviour and thus what kind of monitoring is required.
- Insight in the effects of control on overall system behaviour
- Learning the importance of non-linearities both in the systems themselves as well as in the control systems that overlay them

The outstanding advantage of simulation models is that complex systems for which it is not affordable to put up real hardware in a laboratory or that are in an experimental phase or even systems that do not exist, can be introduced into the curriculum in an affordable way.

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