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# On Propagating Requirements and Selecting Fuels for a Benson Boiler ⋆

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**Abstract:** In this paper, the problem of optimal choice of sensors and actuators is addressed. Given a functional encapsulating information of the desired performance and production economy the objective is to choose a control instrumentation from a given set to comply with its minimum. The objective of the work is twofold: reformulation of the business objectives into mathematical terms and providing solution to the given optimization. Commonly, there exist overall business objectives which dictate how a plant should be instrumented and operated either directly or indirectly. The work shows how to propagate a global objective to local subsystems. Particular focus is on a boiler in a power plant operated by DONG Energy - a danish energy supplier. The business objectives have been propagated to the actuator level to allow for selection of an actuator configuration.

Keywords: complex systems, hierarchical systems, hierarchical structures, static optimization problems

## 1. INTRODUCTION

The selection of sensors and actuators has usually depended greatly on the designer's system knowledge, however, in recent years more focus has been made on developing tools to aid the designer during this phase as processes are becoming more complex and difficult to assess. One such tool is the Relative Gain Array, which is used to pair inputs and outputs in a multiple input multiple output system to enable decentralized single input single output control [Skogestad and Postlethwaite, 2005, page 90].

The placement of sensors and actuators has been studied for different applications and [Padula and Kincaid, 1999] reviews methods used in the aerospace industry. More general purpose methods for selecting and placing sensors and actuators have been evaluated in [van de Wal and de Jager, 2001] and [Stephanopoulos and Ng, 2000], which include e.g. methods relying on controllability measures such as state reachability and more sophisticated methods using robust performance measures. It is also concluded in [van de Wal and de Jager, 2001] that the choice of sensors and actuators dictates the expenses for hardware, implementation, operation, and maintenance.

A software requirement specification procedure is presented in [Leveson et al., 1994] which is used on an industrial aircraft collision avoidance system (TCAS II). They conclude that the model used during specification should resemble the real world to allow the designer to used his/her system knowledge.

The requirements for a process control system are specified for the very top level. They reflect cost, reliability, availability, survivability, and dependability. The aim of this work is to investigate how the selection and placement of sensors and actuators influence such measures and eventually how the measures influence the selection and placement of sensors and actuators.

### *1.1 Outline*

This paper presents the first results gained from the case study of a power plant operated by DONG Energy. The objective is to gain an insight into what challenges arise when propagating business objectives to the selection of sensors and actuators. First, an introduction to the problem is given in Section 2 including a presentation of the plant used to illustrate the problem. Thereafter, our approach to propagate the objectives is presented in Section 3 along with some preliminary results on actuator selection for the presented plant. Finally a discussion is made about the results and the future work within this program.

## 2. PROBLEM STATEMENT

The top level business objectives for DONG Energy deal with Efficiency, Availability, Controllability, and Life Time but the ultimate goal is to maximize DONG Energy's profit. In the collaboration with DONG Energy a coal fired boiler - a vital component of a power plant - is used in a test process as it possesses many of the aspects for propagating business level objectives to subsystem requirements

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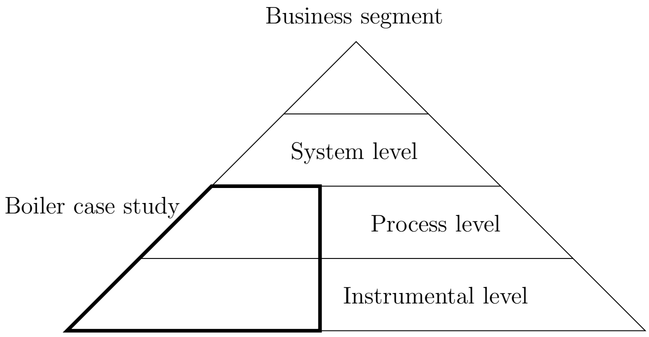


Fig. 1. Business hierarchy showing the location of the boiler case study.

and thus in selection of sensors and actuators. Figure 1 illustrates how the boiler is placed in an overall business hierarchy.

The model considered in this paper consists of the following components:

**Coal mills** The coal mills grind the coal to small dust particles which burn quickly and efficiently. However, it is difficult to control the amount of dust the coal mills deliver as it is not possible to measure the dust flow into the furnace.

**Furnace** The furnace is a module where the coal dust (or other fuels) is burned thereby delivering heat to the boiler.

**Evaporator** The evaporator is fed with water, which is evaporated under high pressure by the heat from the burners.

**Superheater** The superheater (super) heats the steam from the evaporator.

**Economizer** The economizer uses some of the remaining heat in the flue gas to preheat the feed water before it enters the evaporator.

The individual parts of the model are illustrated in Figure 2. However, the model does not consider the flue gas cleaning and smoke stack. Furthermore, the conversion from steam power to electrical power is also omitted but it is assumed that when running at full load the electrical power produced will amount to $400MW$.

To simplify this test process it is chosen to focus on the actuators in the system and the current model is added two additional fuels, which are gas and heavy oil. Some characteristics of the different fuels are:

**Coal** is advantageous when considering the price per Giga Joule (GJ) of stored energy, however, it is difficult to control as the nature of the coal mills introduces fluctuations in the coal flow, which are impossible to measure. This implies that changing the operating point of the system should be done slowly. Furthermore, the coal mills use some electrical energy to grind and dry the coal which needs to be considered.

**Gas** arrives at the power plant under high pressure which is lowered using a turbine generating electrical energy. Furthermore, gas is more expensive than coal and energy within the gas is not converted to steam as efficient as with coal due to the layout of the chosen boiler.

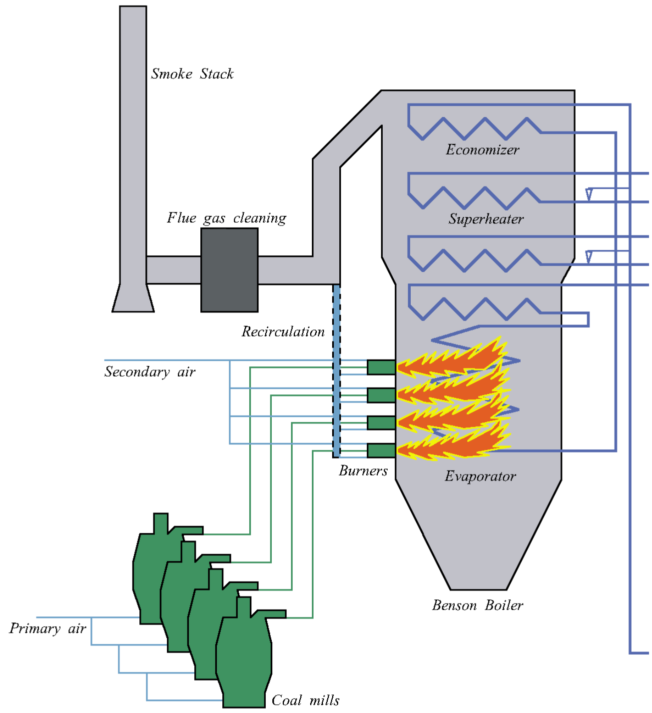


Fig. 2. Benson boiler model.

However, gas is much easier to control as it is possible to measure the flow.

**Heavy oil** is, with the current market prices, the more expensive of the three fuels but does have other advantages; it is possible to measure the oil flow into the boiler. However, it needs to be heated before entering the boiler and this requires energy placing oil between gas and coal when considering the own-consumption.

To get a better view of the different subsystems and their interaction the boiler model has been divided in a hierarchical manner depicted in Figure 3 (only the fuel part has been completed to actuator level). Using this breakdown of the boiler model it is possible to determine how to propagate requirements from boiler level to the individual actuators and ideally this propagation and selection would happen automatically[1].

## 3. PERFORMANCE SPECIFICATION

In this paper the idea is to propagate the business objectives to the bottom of the hierarchy manually by setting up functions relating the objectives to the input and output of the system. If possible this task should with time be automatic or at least some framework aiding the designer in this task should be developed, however, in this paper a heuristic approach has been applied using DONG Energy's system knowledge. The functions should map to some monetary value of using the different fuels in relation to the business objectives and thus enable selection of an actuator configuration. Some of the parameters reflecting the different objectives change in time, e.g. the prices of the fuels and the demands of the electrical market. However, in this paper a certain market situation is considered and

[1] In this paper the system knowledge of the DONG Energy collaborators is used.

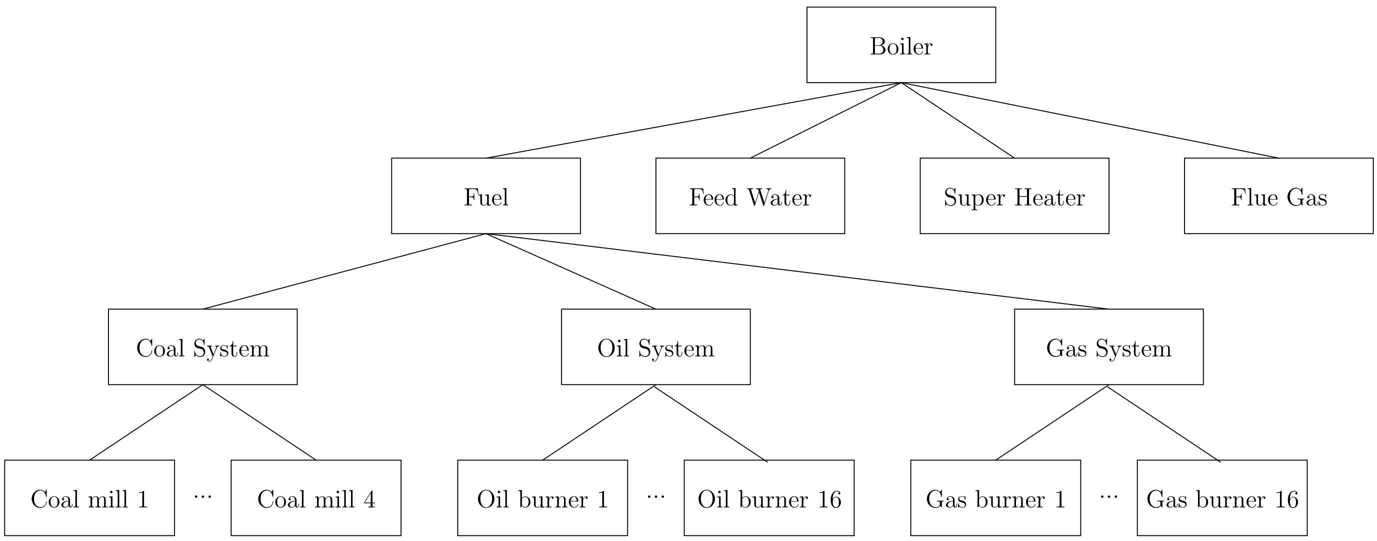


Fig. 3. Example of how a boiler consists of multiple subsystems which can be used to propagate requirements from boiler level to the individual subsystems.

thus the problem becomes a static optimization problem. Furthermore, the functions set up is affine (or close to) and it is therefore chosen to use a linear programming framework to solve the optimization problem.

Three of the business level objectives - Efficiency, Availability, and Controllability - have been translated directly to the actuator level, i.e., simple functions describing the objectives in terms of the individual fuels have been established. Each fuel system comprises multiple sensors, actuators, and control loop, however, they are seen as individual actuators in this paper.

### 3.1 *Efficiency Objective*

Bearing in mind that the focus is the fuel system a high efficiency is desirable as less fuel will be needed yielding less expenses. Certainly, the expenses also depend on what kind of fuel is used as the market prices for gas, oil, and coal are not the same. Furthermore, the three fuels have different efficiency in converting the energy stored in the fuel into steam/electricity [2]. The costs of preprocessing of the three fuels is also different as mention earlier.

In this paper the income from production has been set to $200\frac{dkk}{MWh}$ which was approximately what DONG Energy was paid when this study was established. The fuel prices have been set at $72\frac{dkk}{MWh}$, $104\frac{dkk}{MWh}$, and $180\frac{dkk}{MWh}$ for coal, gas, and oil respectively (these prices were taken from a DONG Energy document). Furthermore, the preprocessing costs have been evaluated as constant loss or gain in energy. Each coal mill uses approximately $1MW$, however, the energy consumption is dependent on the load of the mill but in this paper the total consumption of the four mill is modelled as a constant loss of $4MW$. No data has been found on the energy consumption of the heater used for the oil but it is regarded as substantially lower than the coal mills and has therefore been set to $1MW$. Finally, the gas turbine used to lower the gas pressure generates $5MW$.

The efficiency has been found from measurement data from two power stations operated by DONG Energy and a function has been fitted to the measurement data for each fuel. The total expenses is calculated as total energy produced divided by the efficiency, i.e., the efficiency objective has been modelled as

$$J_e(\boldsymbol{x}) = 200\frac{dkk}{MWh}\boldsymbol{x} - \begin{bmatrix} \dfrac{(x_{1:4}+4MW)72\frac{dkk}{MWh}}{0.00018x_{1:4}+0.44} \\ \dfrac{(x_{5:20}-5MW)104\frac{dkk}{MWh}}{0.00031x_{5:20}+0.37} \\ \dfrac{(x_{21:36}+1MW)180\frac{dkk}{MWh}}{0.00018x_{21:36}+0.37} \end{bmatrix} \quad (1)$$

where $\boldsymbol{x}$ is the load in $MW$ of four coal mills, 16 gas burners, and 16 oil burners respectively. Figure 4 depicts graphs of function $J_a$ (when the cost of coal, gas, and oil is added individually) and as seen coal is the only fuel yielding any income when only considering the efficiency objective. That is the price of gas and oil is too high when only considering the stored energy and discarding other benefits these fuels have.

### 3.2 *Controllability Objective*

A power plant is not only paid by the amount electricity produced but also the capability to change production as the available power always needs to fit the current demand of the electrical market. The ability to change production has, therefore, also a certain monetary value or income for a power plant. An expense associated to controllability is the fluctuations in the production, i.e., if a plant produces too little or too much power it is penalized.

The changes possible with the plant considered is depicted in Figure 5, i.e., when running the plant in the interval $[0MW,\ 200MW]$ and $[360MW,\ 400MW]$ it is

[2] The different efficiencies are assumed to be caused by the manner the individual fuels burn

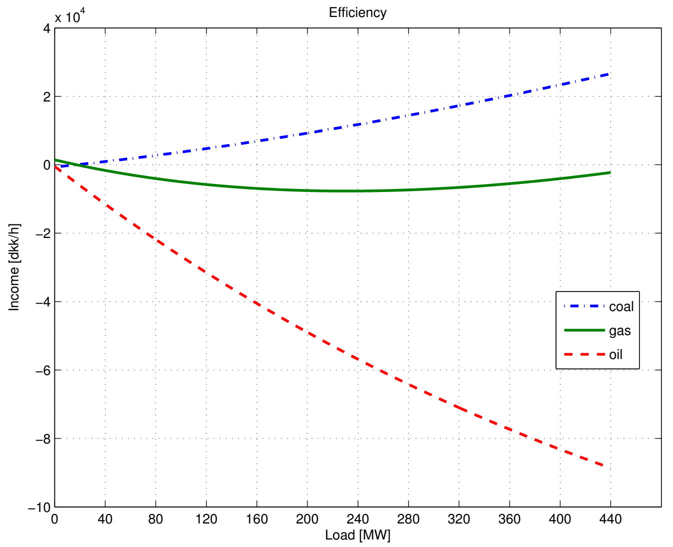


Fig. 4. Graph of the income from the efficiency objective of the three different fuels. The horizontal axis illustrates the plant production in $MW$ and the vertical axis denotes the income per hour, $\frac{dkk}{h}$.

possible to change the load with $2\frac{MW}{min}$ and in the interval $[200MW,\ 360MW]$ it is possible to change the load with $4\frac{MW}{min}$ and $8\frac{MW}{min}$ for coal and gas/oil respectively. These limits are set from the ability to control the different fuels and temperature constraints in the boiler, i.e., in order not to stress the metal in the boiler temperature gradients need to be under a certain limit which is ensured by using these limits. Functions describing the possible change for

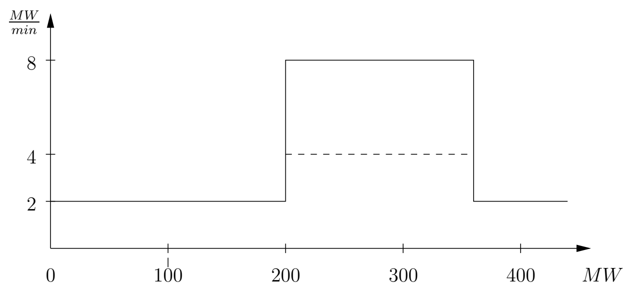


Fig. 5. Possible load changes given certain running load (solid: gas/oil, dashed: coal.)

coal, $h_c(l)$, and oil and gas, $h_{go}(l)$, are defined as

$$h_c(l) = \begin{cases} \frac{0.033\frac{MW}{s}}{l}, & 0 < l < 200 \\ \frac{0.067\frac{MW}{s}}{l}, & 200 < l < 360 \\ \frac{0.033\frac{MW}{s}}{l}, & 360 < l < 400 \end{cases} \quad (2)$$

$$h_{go}(l) = \begin{cases} \frac{0.033\frac{MW}{s}}{l}, & 0 < l < 200 \\ \frac{0.133\frac{MW}{s}}{l}, & 200 < l < 360 \\ \frac{0.033\frac{MW}{s}}{l}, & 360 < l < 400, \end{cases} \quad (3)$$

where $l$ is the load in $MW$.

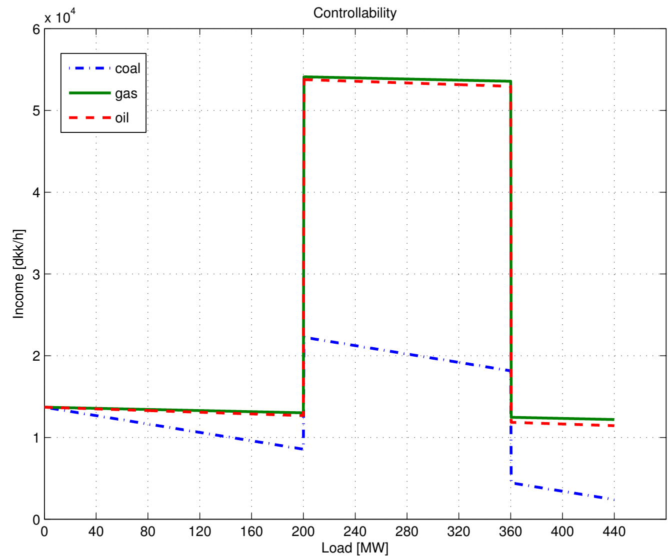


Fig. 6. Graph of the income from the controllability objective of the three different fuels. The horizontal axis illustrates the plant production in $MW$ and the vertical axis denotes the income per hour, $\frac{dkk}{h}$.

The monetary value of the ability to change load has been determined from an internal DONG Energy document stating that it is possible to earn $1000000\frac{dkk}{MW/min}$ each year from this ability. The expense associated to the noise in the output of the system is considered to be proportional to the variance in the output. Furthermore, the variance is assumed to be proportional to the load of the plant. When using oil or gas the plant can be controlled better than when using coal, therefore, the variance of the three fuels have been estimated to $0.015\frac{W^2}{W}$, $0.002\frac{W^2}{W}$, and $0.003\frac{W^2}{W}$ for coal, gas, and oil respectively. The conversion factor from variance to monetary value has been set to the same as for the income - at least in numerical sense. The income from controllability is calculated as

$$J_c(\boldsymbol{x}) = 6850\frac{dkk}{\frac{MW}{s}\cdot h}\begin{bmatrix} h_c\ (l)\boldsymbol{x}_{1:4} \\ h_{go}(l)\boldsymbol{x}_{5:20} \\ h_{go}(l)\boldsymbol{x}_{21:36} \end{bmatrix} - 6850\frac{dkk}{MW\cdot h}\begin{bmatrix} \sigma_c^2\boldsymbol{x}_{1:4} \\ \sigma_g^2\boldsymbol{x}_{5:20} \\ \sigma_o^2\boldsymbol{x}_{21:36} \end{bmatrix} \quad (4)$$

where $\boldsymbol{x}$ is the load in $MW$ of four coal mills, 16 gas burners, and 16 oil burners respectively and $\sigma_c^2$, $\sigma_g^2$, and $\sigma_o^2$ are the variances for coal, gas, and oil respectively as defined above. Figure 6 depicts graphs of the function $J_c$; as seen gas yields the greatest income with regards to controllability - closely followed by oil.

### *3.3 Availability Objective*

The last business objective considered in this example deals with availability which evaluates extra actuation power as it can be used to overcome possible faults in the system.

The available actuation power depends on how many actuators are used, the maximum possible actuation, and as mentioned the current actuation power. The maximum load possible with the different actuators is $532MW$, $452MW$, and $480MW$ for coal, gas, and oil respectively. Furthermore, when using coal four actuators is considered (the four coal mills) and for gas and oil 16 actuators are

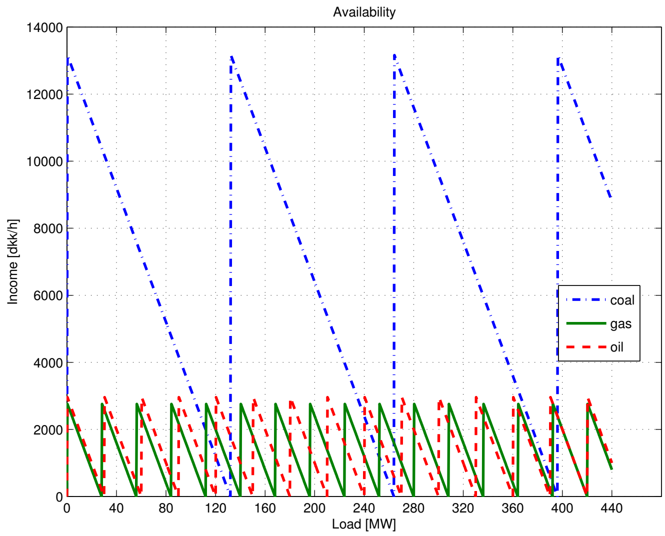


Fig. 7. Graph of the income from the availability objective of the three different fuels. The horizontal axis illustrates the plant production in $MW$ and the vertical axis denotes the income per hour, $\frac{dkk}{h}$.

modelled (the individual burners), i.e., one actuator is sufficient for respectively $133MW$, $28.25MW$, and $30MW$ of production for coal, gas, and oil. Therefore, if a production of more than $133MW$, when using coal, is needed this implies that an additional actuator must be used. In this paper the available actuation power is modelled as

$$h_a(\boldsymbol{x}) = \begin{bmatrix} 133\frac{MW}{act} \cdot \mathbf{1}_{4x1} - \boldsymbol{x}_{1:4} \\ 28.25\frac{MW}{act} \cdot \mathbf{1}_{16x1} - \boldsymbol{x}_{5:20} \\ 30\frac{MW}{act} \cdot \mathbf{1}_{16x1} - \boldsymbol{x}_{21:36} \end{bmatrix}, \quad (5)$$

where $\mathbf{1}_{axb}$ is a matrix with $a$ rows and $b$ columns all with ones, and $\boldsymbol{x}$ is the load in $MW$ of coal, gas, and oil respectively. The monetary value has been priced to $400\frac{dkk}{MW \cdot h}$ which yields a maximum income of approximately half of what is possible from production.

The income from availability is calculated as

$$J_a(\boldsymbol{x}) = h_a(\boldsymbol{x}) \cdot 400\frac{dkk}{MW \cdot h}. \quad (6)$$

Figure 7 depicts graphs of the function for availability for the three different fuels when the minimum number of actuators of are used.

### 3.4 Total Income

When choosing a fuel it is necessary to evaluate all of the objectives and as each of them returns a monetary value they can be added. The selection of which fuel to use can then be based on which fuel yields the greatest overall income. The total income is

$$J_t(\boldsymbol{x}) = J_e(\boldsymbol{x}) + J_c(\boldsymbol{x}) + J_a(\boldsymbol{x}), \boldsymbol{x} \in \mathbb{R}^{36}, \quad (7)$$

where $J_e(\boldsymbol{x})$, $J_c(\boldsymbol{x})$, and $J_a(\boldsymbol{x})$ are defined in (1), (4), and (6) respectively. Figure 8 shows the graph of the total income function, $J_t(\boldsymbol{x})$, when considering the three different fuels individually and when the minimum number of actuators are used. The function $J_t(\boldsymbol{x})$ for the production of the individual actuators in $MW$ gives income per hour, $\frac{dkk}{h}$.

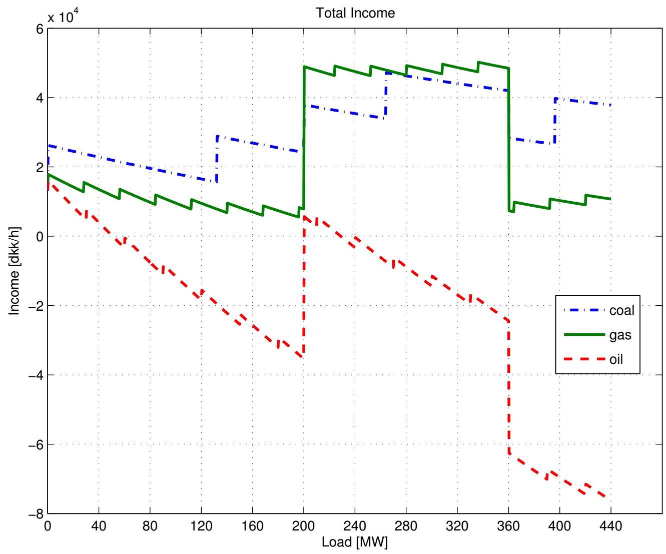


Fig. 8. Graph of the total income of the three different fuels when combining the three objectives. The horizontal axis illustrates the plant production in $MW$ and the vertical axis denotes the income per hour, $\frac{dkk}{h}$.

As seen in the figure coal yields the greatest income in low load and high load, however, there are loads where gas yields the greatest income and thus it is preferable. This is, however, evaluated by assuming that the minimum number of actuators is used e.g. when using coal if the total load is below $133MW$ only one actuator is used. This assumption is used to simplify the calculations of the total income.

### 3.5 Mixing Fuels

It is possible to investigate the monetary benefit of mixing fuels when considering the contribution in load from the three fuels (36 actuators) as a linear combination yielding the desired total load. The optimal cost of using a mixture of the 36 actuators can be calculated as

$$J_m(l) = \max_{\boldsymbol{\alpha} \in \Delta} \Sigma J_t(\boldsymbol{\alpha} \times \boldsymbol{x}) \quad (8)$$
$$s.t. < \boldsymbol{\alpha}, \boldsymbol{x} >= l$$

where $\times$ denotes the schur-product or element by element product,

$$\Delta = \left\{ \boldsymbol{\alpha} \in \mathbb{R}^{36} \mid \sum_{i=1}^{36} \alpha_i = 1, \alpha_i \geq 0 \right\}, \quad (9)$$

$\boldsymbol{x}$ is the load in $MW$ of coal, gas, and oil respectively, $\boldsymbol{\alpha}$ denotes the mixing ratio of 4 coal burners, 16 oil burners and 16 gas burners, $l$ is the desired total production load and $J_t(\boldsymbol{x})$ is defined in (7). By solving this optimization problem it is possible to choose which of actuators that should be used. If a actuator is not included in the optimal mix then it can be discarded.

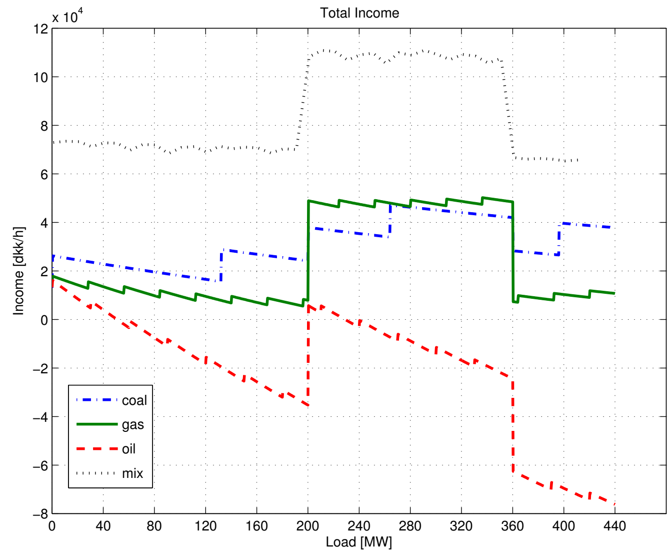


Fig. 9. Graph of the total income possible when mixing oil and coal. The horizontal axis illustrates the plant production in $MW$ and the vertical axis denotes the income per hour, $\frac{dkk}{h}$.

The optimization problem is formulated in the linear programming framework such that YALMIP [3] can be used to solve the problem. The affine functions have been implemented by introducing auxiliary variables and equality constraints. Furthermore, an upper bound has been imposed on the income for extra available actuation power, i.e., $J_a$ is bounded. The motivation is that given a certain market situation only a limited amount of extra actuation has a value.

A graph of $J_m(l)$ is depicted in Figure 9 along with the total income of the individual fuels. As seen in the figure it is possible to obtain a higher income when mixing the fuel types in an optimal manner. This is believed to be due to the extra controllability and availability obtain in the mixed fuel. The limit in availability was set to $150MW$.

The actuator configuration and loads of the individual actuators proposed by the algorithms at $100MW$, $200MW$, and $400MW$ is given in below.

**100MW:** At $100MW$ load production 5 actuators are used. 1 coal mill at $100MW$, 2 gas burners at $0MW$, and 2 oil burners at $0MW$.

**200MW:** At $200MW$ load production 10 actuators are used. 0 coal mills, 8 gas burners at $25MW$, and 2 oil burners at $0MW$.

**400MW:** At $400MW$ load production 11 actuators are used. 2 coal mills at $133MW$, 8 gas burners at $4{\cdot}28MW$, $23MW$, and $3 \cdot 0MW$, and 2 oil burners at $0MW$.

As seen the configuration changes as the load of the power plant is changed. Thus to find the actuators needed to run the power plant such that the greatest income is generated the configuration at all the desired loads must be evaluated and the minimum configuration can then be found. However, it would also be possible to evaluate if anything is gained by e.g. adding 4 gas burners to a coal fired plant. In this example the optimal configuration is to equip the plant with 2 coal mills, 8 gas burners, and 2 oil burners.

[3] YALMIP is a toolbox for Matlab which can be used defining and solving optimization problems

## 4. DISCUSSION AND FUTURE WORK

This paper has presented a manually hierarchical breakdown of a boiler model, which is used to determine how business level objectives can be propagated to the individual subsystems. A business model of the top level objectives have been established using simple functions of the input and output of the system. Given a certain production load the functions return an income in $\frac{dkk}{h}$ which can be used to select which fuel to use under different operation conditions. Using the business model a maximization problem has been posed which yields the greatest possible income when mixing three different fuels. The maximization problem has been solved using the YALMIP toolbox to find the optimal actuator configuration at different production loads.

Future work include developing formal methods which can be used for propagating the business objectives and determining how different sets of sensors and actuators should be evaluated such that an optimal selection can be performed.

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