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Model-based assessment of energy-efficiency, dependability, and cost-effectiveness of waste heat recovery systems onboard ship

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ABSTRACT

Technological systems are not merely designed with a narrow function in mind. Good designs typically aim at reducing operational costs, e.g. through achieving high energy efficiency and improved dependability (i.e. reliability, availability and maintainability). When there is a choice of alternative design options that perform the same function, it makes sense to compare alternatives so that the variant that minimises operational costs can be selected. In this paper, we examine this issue in the context of the design of Waste Heat Recovery Systems (WHRS) for main engines of large commercial freight vessels. We propose a method that can predict the operational cost of a WHRS via thermodynamic analysis which shows costs related to energy utilisation, and dependability analysis which shows costs related to system unavailability and repair. Our approach builds on recent advances in thermodynamic simulation and compositional dependability analysis techniques. It is a model-based approach, and allows reuse of component libraries, and a high degree of automation which simplify application of the method. Our case study shows that alternative designs can be explored in fast iterations of this method, and that this facilitates the evidence-based selection of a design that minimises operational costs.

1. Introduction

Minimising operational costs is a worthwhile goal for most industrial systems. We contextualise this goal within current developments in the regulatory and technological environment in the shipping industry. A major part of the operating cost of ocean vessels is directly related to fuel oil. This cost can be reduced by improving energy efficiency, clearly an area where economics aligns with environmental concerns. The move for energy efficiency is indeed also driven by increasingly tight environmental regulations, specially by the IMO and EU, aiming at the reduction of CO_2 emissions (Lampe and Freund, 2013).

Combustion engines onboard ship, only convert around 50% of the fuel energy into propulsion. The other half is lost to the environment mainly as heat energy via the cooling system (~20%) and the exhaust gas system (~25%). The heat energy contained in exhaust gases is partly recoverable via use of Waste Heat Recovery Systems (WHRS) (MAN Diesel & Turbo, 2012). Currently, WHRS can boost the energy efficiency of the main engine by more than 10%. This is achieved by generating electrical power to serve electrical consumers and/or acting as additional power source for propulsion through a shaft motor.

The topic of WHR has already been addressed in the textbooks Reay (1979), Thumann (1983) and Goldstick and Thumann (1985) over 30 years ago. A survey for the US department of energy (Energetics, 2004) reviewed energy recovery in industrial energy systems, and Junior et al. (2016) compiled current research in Energy Management, Air Conditioning and WHR in conference proceedings. Recent work with a special focus in maritime applications can e.g. be found in Adamkiewicz and Wietrzyk (2012) with an overview over currently available WHR systems regarding efficiency and savings; whereas in Zou et al. (2013) detailed model simulations are validated by available measurements.

WHRS introduce energy and cost gains but also entail new costs: purchase and installation costs, as well as costs related to their failure, repair and maintenance. To estimate the latter, dependability analysis of the system is required so that costs related to failure and repair can be established. This in turn can feed into calculations on payback period and cost savings from the introduction of a WHRS. Dependability analysis encompasses prediction of reliability and availability and should take maintenance into account as it prolongs the useful life of the system. Indeed, reduced availability will have significant impact on costs, especially if repairs cannot be executed at sea, but require the ship to reach

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Abbreviations

T	Temperature (K)
ΔT	Temperature difference (K)
$\dot{m}$	Mass flow (kg s^{-1})
p	Pressure (N m^{-2})
c_P	Specific heat capacity (J kg^{-1} K^{-1})
P	Power (J s^{-1})
h	Specific enthalpy (J kg^{-1})
$\dot{Q}$	Heat flow (J s^{-1})
η	Efficiency
γ	Specific heat ratio
λ	Failure rate
Exc	Excess output (deviation class)
$F(t)$	Failure probability (unreliability)
FTA	Fault Tree Analysis
HE	Heat Exchanger
HFO	Heavy Fuel Oil
HP	High Pressure
HRSG	Heat Recovery Steam Generator
$\dot{L}$	Mechanical power (W)
LP	Low Pressure
Low	Low output (deviation class)
LowLow	Very low output (deviation class)
MCR	Maximum Continuous Rating
MCS	Minimal Cut Set
MDO	Marine Diesel Oil
ME	Main Engine
Om	Omission of output (deviation class)
PT	(Exhaust gas) Power Turbine
$Q(t)$	Unavailability
$R(t)$	Reliability
Red	Reduced output (deviation class)
ST	Steam Turbine
ST1	Single pressure Steam Turbine
ST2PT	Combined dual pressure Steam Turbine with Power Turbine
t	(Operational) time
WHRS	Waste Heat Recovery System

the next harbour or even to go to dry dock.

In the past, researchers have performed reliability, availability and cost analysis of energy systems. Haghifam and Manbachi (2011) have proposed a methodology for the thermal and electrical reliability and availability analysis of combined heat and power (CHP) systems. The method was based on Markov model and it considered three important subsystems of the CHP namely the electricity-generation, fuel-distribution, and heat-generation subsystems. On the other hand, Wang et al. (2013) used Markov model to perform reliability and availability analysis of redundant building cooling, heating and power (BCHP) system. It was showed that the redundant design of the BCHP is more reliable than the non-redundant BCHP design. As these approaches used Markov model for reliability analysis, for general application they may suffer from state-space explosion. Koeppel and Andersson (2009) proposed a method for reliability modelling of multi carrier energy systems. In the analysis, the authors consider the dependency and redundancy introduced due to the mutual conversion among different energy sources (e.g., thermal to electrical energy), and evaluate the reliability of supply in terms of the reliability characteristics of the existing conversions. Similar research on reliability and availability analysis of different types of energy systems and their hybrid forms could be found in (Collins et al., 2009; Tian and Seifi, 2014; Zhao et al., 2017). To assist with the optimization of the design and performance of energy systems, a method for thermoeconomic analysis of energy systems was presented in (Tsatsaronis, 1993). However, this technique did not take reliability into consideration during the analysis. Nagarajan et al (2013) have performed a reliability and cost analysis for optimising renewable energy sources.

In this paper, we propose a novel method that can be used to predict the operational savings and costs of a WHRS via thermodynamic and dependability analysis. Thermodynamic analysis throws light on savings and costs related to energy utilisation. Dependability analysis shows the costs arising from system unavailability. The proposed approach builds on recent advances in thermodynamic simulation and compositional dependability analysis techniques. It is a model-based approach which employs component libraries and facilitates a high degree of automation. These properties in turn simplify application of the method and its iterations. Using this approach, decision makers may perform swift studies of different possible WHRS variants to select the best, i.e. the cost-optimal variant for installation.

Thermodynamic analysis exploits computational models of WHRS components which have been encoded using the “Ship Energy Systems” library (Lampe and Freund, 2013; Freund et al., 2014) of SimulationX tool (ESI ITI GmbH, 2017), which is based on the Modelica language. The dependability analyses of WHRS variants are done using HiP-HOPS (Hierarchically Performed Hazard Origin and Propagations Studies) (Papadopoulos et al., 2001, 2016). This is a state-of-the-art, model-based technique in which a system model augmented with component failure data drawn from libraries is used as basis for auto-calculation of system fault trees from which dependability is established. Energy efficiency and dependability predictions are then translated to costs and overall economic performance of a WHRS. This type of analysis can be used to compare different WHRS architectures. The proposed method is novel and efficient in application and iteration thanks to its model-based nature, the reusability and compositionality of the libraries used in the analysis as well as the automated algorithms that can be run on the models.

In section 2, a number of possible configurations for WHRS is given. The key components of a WHRS system are explained and a discussion follows on how they can be put together in a number of different candidate WHRS architectures for evaluation. Section 3 proposes a method for analysis and selection of an optimal WHRS architecture. The focus is on thermodynamic and dependability analysis of the architecture and the translation of results to savings and costs arising assuming a specific operational scenario. Economic performance is ultimately used as criterion for selection among a set of possible WHRS architectures. We show that the analysis of each architecture reuses thermodynamic and failure models of more basic WHRS components. Section 4 focuses on thermodynamic and failure modelling at component level where such reuse is possible. Section 5 applies the method to a set of different WHRS architectures assuming a range of operational scenarios. Finally, in the light of results from the case study, in Section 6 conclusions are drawn.

2. Architectures for WHRS

Incorporating a WHRS leads to an increase of the ship's energy efficiency for significant main engine loads. Different WHRS solutions are available for ship operations, and when designers choose one they consider a number of factors which include engine power, electrical power demand, ratio of engine loads, available space in engine room, emissions requirements and payback time (MAN Diesel and Turbo, 2012).