Data-driven sustainable ship design using Axiomatic Design and Bayesian Network Model

G Fardelas[1,2] **and S G Kim**[1,3]

[1] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2] System Design and Management Program, Massachusetts Institute of Technology, Cambridge, MA 02139, US
[3] Corresponding author's email: sangkim@mit.edu

Abstract. Environmental sustainability, as well as social and economic well-being, must be considered in every stage of a product lifecycle, from conceptual design to its retirement. Even though this sustainability-centric approach represents a critical driver for innovation, it also increases the design complexity. Nowadays, the maritime transport accounts for a large share of transport demand, and the importance of sustainable ship design is increasingly growing, not only for ethical and legislative but also for competitive reasons. The design of a sustainable ship considering all those aspects is a complex process in this regard. One way to manage the complexity is to identify and avoid the functional couplings at the early stage of the design process. This paper presents the conceptual design of a merchant ship's conventional propulsion system with a view to the Axiomatic Design framework and known sustainable engineering principles. We also explore the Bayesian machine learning interface to propose a data-driven method for calculating the probability of achieving specific sustainability-related functional requirements. Data-driven Bayesian reasoning can also be used to select the best design parameter among the proposed alternatives as well as to identify hidden design couplings that have not identified by the designers in the conceptual design stage.

1. Introduction

The design of ships has been a process that dates back thousands of years. In the past, it was more of an art than science, based on heuristic experience and trial-and-error design methods. Given the importance of solving the ship design problem, trial-and-error methods have been replaced by a system-based approach, which considers a ship as a system integrating various subsystems and their components (e.g., ship propulsion, navigation systems, and arrangements). The objective of this work is to present the conceptual design of a merchant ship's conventional propulsion system with a view to known sustainable engineering principles in the Axiomatic Design (AD) framework.

Ships are large systems not only because they are physically large in size, but also, they have various FRs to be met throughout their life cycle. Ships are also time-variant systems as they have many FRs at the highest level, but only a subset of these FRs must be satisfied at a given time, while different subsets need to be satisfied at different points in time. As a result, a ship as a system must reconfigure itself to satisfy different subsets of FRs throughout its life cycle.

The design of ship has been an iterative decision-making process that often reflects the conflicting interests of the various stakeholders. Additionally, the surging trend of digitalization in the maritime sector and the urgent requirement for a more sustainable world push for designs that can reduce the complexity of ship design in the context of ethical responsibility, legislative compliance, and fair market

competition. One way to manage the complexity and control the design of a system is to identify and manage the potential functional couplings at the early stage of the design process [1]. The evolution of Systems Engineering has encouraged the development of various design methods applicable to ship design, such as the "set-based design" and the "analytic hierarchy process (AHP)". In practice, these methods drive to an ad hoc approach to the conceptual design or give priority only to some FRs without checking their dependency, resulting in a complex design that can negatively affect system's quality attributes such as reliability, maintainability, and flexibility. Nevertheless, sustainable design requires for managing or even restricting design's complexity. The sustainability imperative requires insight into a Human–Environment system [2], which would increase the design's complexity as it demands in-depth knowledge of new interrelationships between science, society, and environment. The holistic approach of AD is ideal to accommodate the challenges related to sustainable ship design.

The paper shows a scalable example for the total ship design following sustainable engineering principles in two aspects: 1) Axiomatic Design as a methodology to control the complexity of sustainable ship design and 2) Bayesian machine learning technique as a supportive tool for improving system's architecture and assessing system's sustainable impact.

2. Intersection of sustainability initiative and ship design

Ships are built to cover society's needs through the provision of specific (commercial or noncommercial) services. Simultaneously, demand for maritime transport grows in parallel with the world population, industrial activity, and trade growth. Maritime transport will continue to account for the largest share of demand, with a contribution of 75% in 2050 [3]. Changes in the structure of energy markets and fuel industry, the volatility of energy prices, piracy and security concerns, automation, big data technology, and shipping profitability along with the 2030 Agenda for Sustainable Development (ASD), and the Paris Agreement on climate change require a balanced approach between contradicting economic, social and environmental objectives.

According to the book, "Our Common Future" from the UN committee, sustainable development is defined as the development that meets the needs of the present without compromising future generations' ability to meet their own needs [4]. Within this scope, a sustainable design outcome should consider all environmental impacts throughout its life cycle (from concept design to recycling), including social and economic well-being, without compromising cost, appearance, and quality attributes. This approach also applies to ship design. This paper focuses on designing at concept level a ship's conventional propulsion system that is compatible with the fuels currently prevalent in the maritime sector, providing at the same time an environment-friendly and energy-efficient solution without sacrificing the profitability of the shipping industry.

3. Application of Axiomatic Design on sustainable ship design

3.1. Conceptual design of a merchant ship's conventional propulsion system: Design hierarchies
Once the ship's total resistance has been estimated, the next steps of designing a vessel's propulsion system are the choice of the propulsor and its matching with the hull and the prime mover (propulsion engine). Assuming a fixed-pitch propeller, the decomposition of the design problem results in the FR and DP hierarchies as shown in Table 1. The system architecture is described by the design equations (1) to (8).

The design of a ship's propulsion system in the context of the Axiomatic Design begins with analyzing the operational requirements that are common to each type of propulsion plant. At the highest level of design, we need a system that can move the ship in the water, overcoming its total resistance. In addition to producing thrust, the propulsion system consists of individual parts whose function is to seal the system with the marine environment and hold the system in place under extreme weather conditions. The shaft system must transmit the power generated by a sustainable main engine to the propeller, whose rotational motion is converted into thrust. The propulsion system's components must

also be supported and interconnected and must comply with the existing regulations of the International Maritime Organization (IMO).

Table 1. FRs and DPs of the sustainable propulsion system.

ID	FR	DP
1	Move through water	Propulsion system
1.1	Produce thrust	Drivetrain with engine
1.1.1	Convert power into thrust	Propeller
1.1.2	Generate sustainable rotary power	Sustainable main engine
1.1.2.1	Machinery system that meets NOx regulation	Dual fuel engine
1.1.2.2	Machinery system that meets SOx regulation	Low sulfur combustion system
1.1.2.3	Machinery system that meets EEDI regulation	Fuel injection system
1.1.3	Transmit power	Shaft system
1.1.3.1	Transmit power from main engine to thrust shaft	Engine-thrust shaft coupling
1.1.3.2	Transmit power from main engine-thrust shaft coupling to propeller	Shaft arrangement
1.1.3.2.1	Receive the rotational motion from the crankshaft	Thrust shaft
1.1.3.2.2	Receive the rotational motion from the thrust shaft	Intermediate shaft
1.1.3.2.3	Receive the rotational motion from the intermediate shaft	Tail shaft
1.2	Seal components	Stern tube sealing arrangement
1.3	Fix components	Mounting system
1.3.1	Fix main engine	Main engine mounts
1.3.2	Support shaft's load	Bearings system
1.3.2.1	Support thrust shaft's load	Thrust blocks
1.3.2.2	Support intermediate shaft's load	Intermediate shaft mounted bearings
1.3.2.3	Support tail shaft's load	Stern tube
1.3.3	Connect adjacent shafts	Shaft couplings

$$\{FR_1\} = (X)\{DP_1\} \tag{1}$$

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \end{Bmatrix} = \begin{pmatrix} X & O & O \\ O & X & O \\ O & O & X \end{pmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} FR_{1.1.1} \\ FR_{1.1.2} \\ FR_{1.1.3} \end{Bmatrix} = \begin{pmatrix} X & O & O \\ X & X & O \\ X & X & X \end{pmatrix} \begin{Bmatrix} DP_{1.1.1} \\ DP_{1.1.2} \\ DP_{1.1.3} \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} FR_{1.3.1} \\ FR_{1.3.2} \\ FR_{1.3.3} \end{Bmatrix} = \begin{pmatrix} X & O & O \\ O & X & O \\ O & O & X \end{pmatrix} \begin{Bmatrix} DP_{1.3.1} \\ DP_{1.3.2} \\ DP_{1.3.3} \end{Bmatrix} \tag{4}$$

$$\begin{Bmatrix} FR_{1.1.2.1} \\ FR_{1.1.2.2} \\ FR_{1.1.2.3} \end{Bmatrix} = \begin{pmatrix} X & O & O \\ X & X & O \\ X & O & X \end{pmatrix} \begin{Bmatrix} DP_{1.1.2.1} \\ DP_{1.1.2.2} \\ DP_{1.1.2.3} \end{Bmatrix} \tag{5}$$
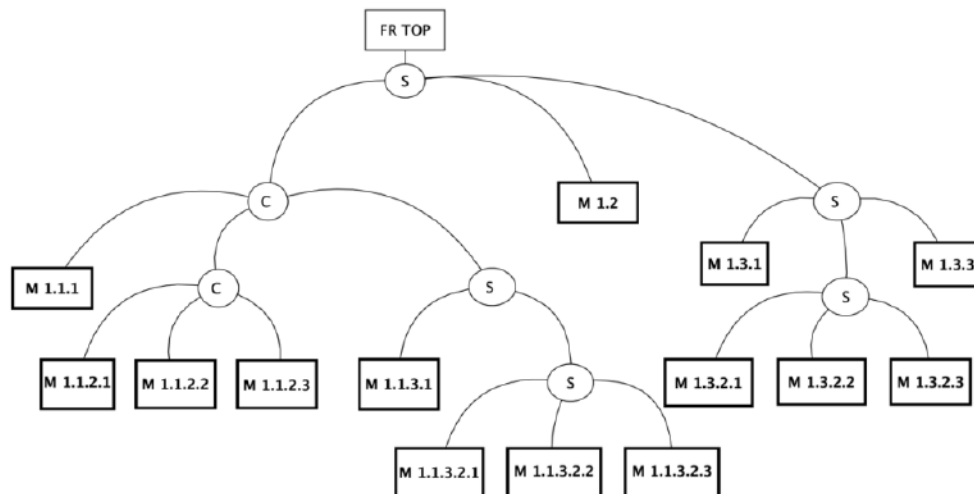
$$\begin{Bmatrix} FR_{1.1.3.1} \\ FR_{1.1.3.2} \end{Bmatrix} = \begin{pmatrix} X & O \\ O & X \end{pmatrix} \begin{Bmatrix} DP_{1.1.3.1} \\ DP_{1.1.3.2} \end{Bmatrix} \tag{6}$$

$$\begin{Bmatrix} FR_{1.1.3.2.1} \\ FR_{1.1.3.2.2} \\ FR_{1.1.3.2.3} \end{Bmatrix} = \begin{pmatrix} X & O & O \\ O & X & O \\ O & O & X \end{pmatrix} \begin{Bmatrix} DP_{1.1.3.2.1} \\ DP_{1.1.3.2.2} \\ DP_{1.1.3.2.3} \end{Bmatrix} \qquad (7)$$

$$\begin{Bmatrix} FR_{1.3.2.1} \\ FR_{1.3.2.2} \\ FR_{1.3.2.3} \end{Bmatrix} = \begin{pmatrix} X & O & O \\ O & X & O \\ O & O & X \end{pmatrix} \begin{Bmatrix} DP_{1.1.2.1} \\ DP_{1.1.2.2} \\ DP_{1.1.2.3} \end{Bmatrix} \qquad (8)$$

3.2. The module junction structure diagram and the data flow chart

Another means of representing the architecture of the system are the module junction structure diagram and the data flow chart [5]. The module junction diagram (Figure 1a) is composed of modules and junctions, which represent FR leaves and their vertical integration respectively. The module junction diagram can be converted to the data flow chart (Figure 1b), which can also express the system architecture showing the data stream flow among modules. The module junction diagram and data flow chart, can be used for understanding of the overall ship design process in terms of the data and information flow and, therefore, can promote sustainable ship design and operation in multiple ways considering its whole life cycle. First, the diagrams can be used in conjunction with failure diagnosis algorithms and can help engineers trace causes of failures, saving sources and time. Second, in project management, the diagrams can provide the roadmap for task coordination and project execution, highlighting how a change in design decisions propagates and affects the system. Third, if the modules are correctly arranged and satisfy the Independence Axiom, a modular ship design can foster professional diversity, as the diagrams can provide the roadmap for stakeholders of different backgrounds located all over the world. Finally, in case the modules, as "providers" of design information, can be linked to sustainability metrics, the diagrams can be the main component of a dynamic sustainability assessment tool for the vessel's whole life cycle.
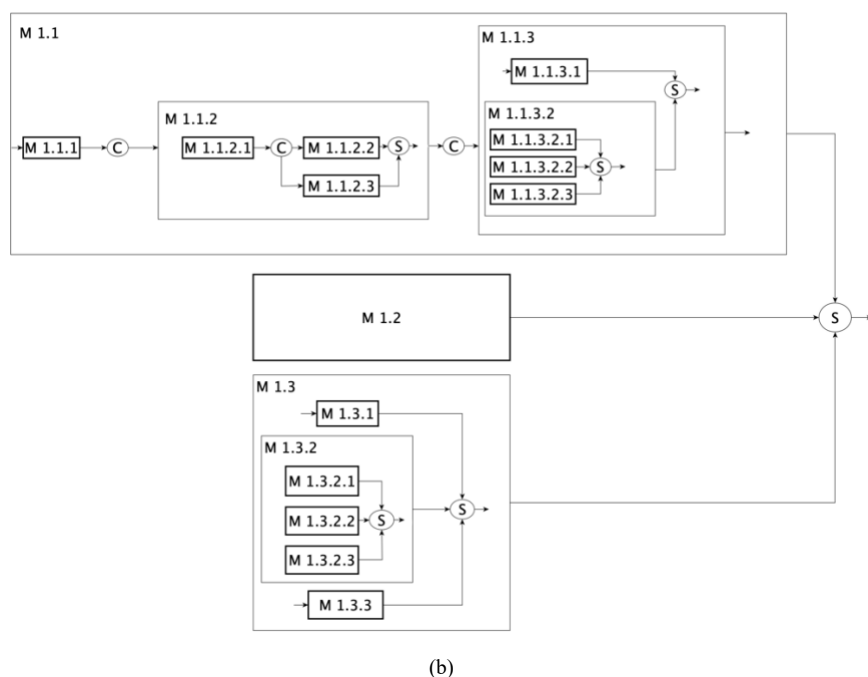

(a)

(b)

Figure 1. The module junction diagram (a) and the data flow chart (b) for the design described by the equations (1) to (8).

4. The interface of Bayesian Networks and Axiomatic Design

4.1. Bayesian Networks overview

Bayesian network (BN) is a probabilistic graphical model that reflects the states of some part of a world being modelled, and describes how probabilities relate to those states. It uses Bayesian inference in order to model conditional dependence, and therefore causation. A Bayesian network is a directed acyclic graph that consists of directed nodes (parent and child nodes) structured hierarchically. The directed arrows connecting the nodes have the probability dependencies between them represented in condition probabilities tables [6].

First, Bayesian networks are useful as they help us model systems of reasonable complexity with a significant computational effort saving, because there is no need to store all possible configurations of states, but only all possible combinations of states between sets of family (parent and child) nodes. After training, the network can help the user identify new or wrong relationships, which can be used for process improvement [7]. Second, a BN is a tool for hybrid intelligence as they combine human learning, in terms of heuristic knowledge provided by domain experts, and machine learning in terms of knowledge learned from data [8]. Third, BNs can support both causal and evidential reasoning, as Bayesian inference allows users to make a prediction of the effects given some causes (causal reasoning) and determine the causes given an observation of the effects (evidential reasoning) [6].

Since AD method and BNs share a similar hierarchical parent-child structure and use the concept of identifying couplings between modules and nodes respectively, we believe that BNs can support AD methodology concerning the design of complex systems that promote sustainability.

4.2. Develop a Bayesian Network for improving system's architecture and assessing its sustainable impact

The information garnered from the decomposition and mapping process between the functional and physical domain can help designers understand design couplings and tradeoffs. However, this information can be evaluated and verified using a data-driven approach to become more useful. Figure 2 shows a compiled BN created using Netica software 6.07 (copyright 1992-2019 by Norsys Software

Corp.) [9]. The network was built using domain knowledge and insight obtained through the decomposition of FRs and DPs (Table 1). Then, it was trained with 750 real cases and its performance was tested with a different dataset of 250 real cases. Each of those 1000 cases corresponds to a ship with a separate propulsion system and operational profile and includes data, which were recorded using sensors [10], [11] or retrieved from ship's technical documentation [11], [12]. The probabilistic relationships among data are represented in the belief bars of the nodes (Figure 2).

The BN does not reflect precisely the hierarchical relationships between FRs and DPs, but being built with knowledge from the decomposition and mapping process, aims to capture the couplings between variables related to FRs, DPs, and system's function, so that it can be used as a supportive tool for designers to ensure or explore the system's sustainable compliance and impact. The network's goal is to help designers quantify some of the elements of the conceptual design matrices and calculate the probability of success for the requirements FR 1.1.2.1, FR 1.1.2.2, and FR 1.1.2.3. These FRs are described by the nodes "NOx Compliance Tier III", "SOx Compliance", and "EEDI Compliance Phase 1" respectively, in the BN of Figure 2.

4.2.1. Bayesian Inference and Independence Axiom. The probability relationships of the nodes of a BN can be validated through the technique of sensitivity analysis. Sensitivity analysis in BNs is a tool to quantify how much a particular node is affected by other nodes. Several advantages have been identified using the sensitivity analysis of a BN, which is built with knowledge obtained from the AD approach. First, the sensitivity analysis can identify design couplings wrongly judged in design matrices or detect hidden design couplings that the designers have not recognized. Second, some sensitivity analysis results, representing the degree of connectivity between nodes related to FRs or DPs, can work as a quantitative measure of the design matrix elements. Table 2 shows the sensitivity analysis results for the "NOx Compliance Tier III" node (relationship with FR 1.1.2.1). Third, the sensitivity results provide a metric of coupling of specific FRs. Table 2 illustrates, for example, the degree of connectivity (equal to 3.9 %) between "NOx Compliance Tier III" (relationship with FR 1.1.2.1) and "SOx Compliance" (relationship with FR 1.1.2.2).

4.2.2. Bayesian inference and Information Axiom. BNs are used by definition to predict the effects given some causes (causal reasoning) and determine the causes given an observation of the effects (evidential reasoning). In the first case, if a node corresponds to a specific FR, BNs can be used to calculate its probability of success and information content, I_i. In the case of evidential reasoning, the Bayesian inference can help designers determine the most possible causes that lead to satisfaction or not of an FR. Figure 3 shows a causal reasoning example, where the network calculates the probability of achieving FR 1.1.2.1 (NOx Compliance Tier III), which equals 0.783, given that the main engine operates with Liquid Natural Gas (LNG) and its rated speed is LOW (80rpm-700rpm for the available data set). The choice of using LNG as fuel presumes the installation of a dual fuel engine (DP 1.1.2.1), while the option of using DIESEL as fuel excludes the dual fuel applications and presumes a diesel single fuel engine. Therefore, the network, using as input the choice of a design parameter (DP 1.1.2.1), returns the probability of achieving its respective functional requirement (FR 1.1.2.1). In the case of evidential reasoning, Figure 4 shows that if we know that the propulsion system is not compliant with the IMO NOx limits (FR 1.1.2.1), then the most probable causes should be the "HIGH" main engine's specific fuel consumption (relationship with DP 1.1.2.3) or /and the "DIESEL" as used fuel (relationship with DP 1.1.2.1). In addition, the module junction diagram and data flow chart, as illustrated in Figure 1, can be used synergistically with the BN casual and evidential reasoning process. Considering the module diagram, we could pinpoint a specific module of interest to apply a BN in quantifying the probability of success in achieving sustainability-related requirements, and at the same time, the data flow chart can be used to guide designers and engineers to where sustainable ship design effort must be focused.
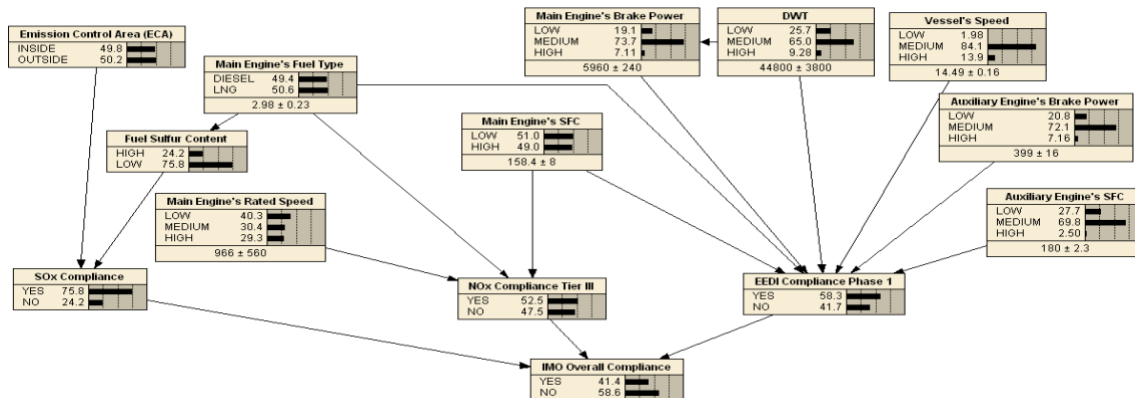
Figure 2. Screenshot of compiled BN for sustainability-related requirements.

Table 2. Sensitivity analysis outcome for the node "NOx Compliance Tier III".

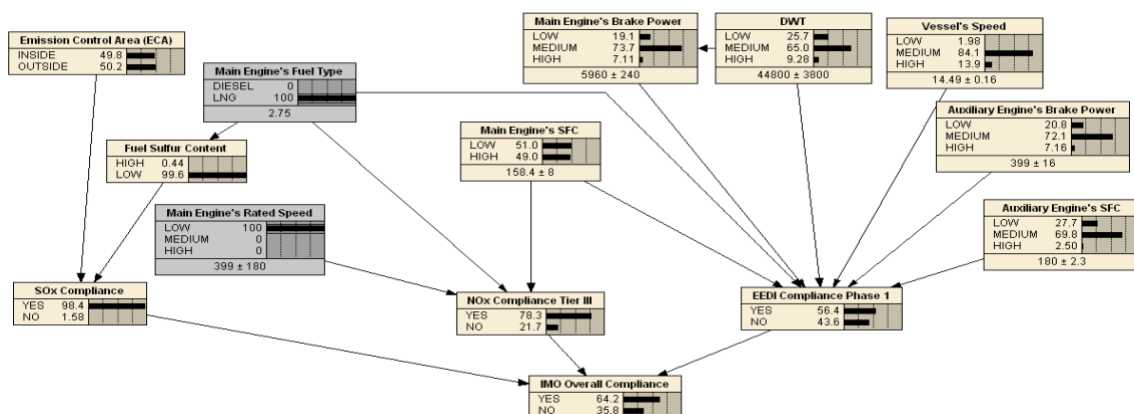| Sensitivity of "NOx Compliance Tier III" due to finding at node:	Percentage
Main Engine's Fuel Type	17
Main Engine's SFC	14
Fuel Sulfur Content	4.33
SOx Compliance	3.9
Main Engine's Rated Speed	0.288
EEDI Compliance Phase 1	0.0257
Auxiliary Engine's SFC	0
Auxiliary Engine's Brake Power	0
Vessel's Speed	0
DWT	0
Main Engine's Brake Power	0
Emission Control Area (ECA)	0

Figure 3. Screenshot of BN when the "Main Engine's Fuel Type" is LNG and "Main Engine's Rated speed" is LOW (causal reasoning).
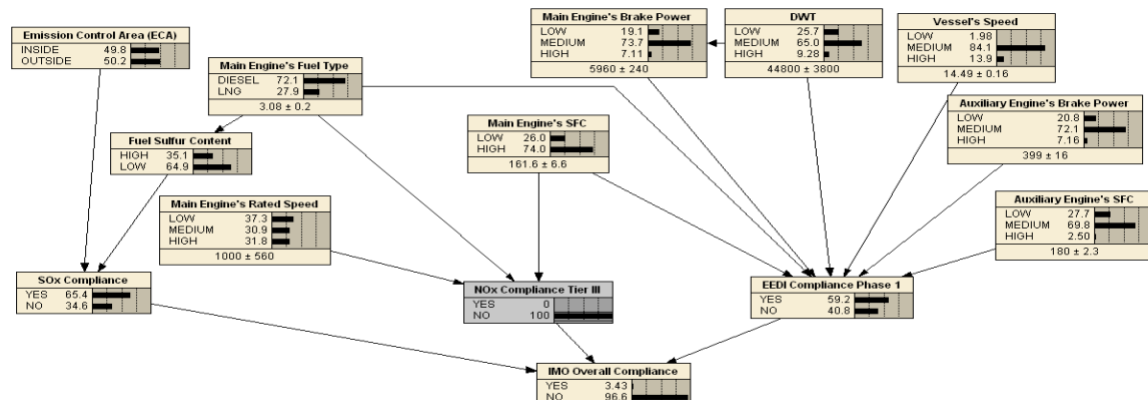
Figure 4. Screenshot of BN when the system does not meet the NOx regulation (evidential reasoning).

5. Conclusion

Sustainable design can increase a system's complexity, which is an inherent challenge in system architecture and is driven by the interconnections and the functional relationships of the system's entities. This paper shows that AD and BNs can be synergistically combined to promote sustainable ship design in two ways. Firstly, the FR-DP diagrams can be used to demonstrate how a change in one of the system's entities affects the others concerning the vessel's sustainable footprint along the life cycle of them. Secondly, the process of forming and mapping the hierarchical structures can be used as the roadmap of building a BN, which after training, can provide data-based feedback for the system architecture and calculate the probability of achieving sustainability-related functional requirements.

References

[1]   Suh N P 2001 *Axiomatic Design: Advances and Applications* (New York: Oxford University Press)

[2]   Jonker G and Harmsen J 2012 *Engineering for Sustainability: A Practical Guide for Sustainable Design* (London: Elsevier Science) p 6

[3]   Psaraftis H N 2019 *Sustainable Shipping: A Cross-Disciplinary View* (Switzerland: Springer International Publishing)

[4]   United Nations World Commission on Environment and Development 1987 *Report of the World Comission on Environment and Development: Our Common Future* (London: Oxford University Press)

[5]   Kim S J, Suh N P and Kim S G 1991 Design of software systems based on axiomatic design *Robot. Comput. Integr. Manuf.* **8** 4, pp 243–55

[6]   Barber D 2016 *Bayesian Reasoning and Machine Learning* (Cambridge, England: Cambridge University Press)

[7]   Ni Z, Phillips L D and Hanna G B 2011 *Evidence Synthesis in Healthcare: Exploring Bayesian Belief Networks Using Netica®* (London: Springer London) pp 293–318

[8]   Li Y, Zhang H, Roy U and Lee Y T 2017 *Proc. 2017 IEEE Int. Conf. on Big Data (Boston)* **1** (Piscataway, NJ: IEEE) pp 1736-1745

[9]   Norsys Sofware Corporation 2021 *Netica Tutorial* (Vancouver: Norsys Software Corporation)

[10]   Stenersen D and Thonstad O 2017 *Report for GHG and NOx Emissions from Gas Fuelled Engines* (Trondheim: SINTEF Ocean AS)

[11]   International Maritime Organization 2016 *Report of the Marine Environment Protection Committee: Amendments to the 2014 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships* (London: IMO)

[12]   Woud H K and Stapersma D 2002 *Design of Propulsion and Electric Power Generation Systems* (London: Institute of Marine Engineering, Science and Technology)