KNOWLEDGE GRAPH BASED DIGITAL TWIN TO SUPPORT GREEN SHIPING

Bill Karakostas[1], Antonis Antonopoulos[2], Takis Katsoulakos[1] Anargyros Mavrakos[1], Theodosis Tsaousis[1]

1 Inlecom Systems, Belgium 2 Konnecta, Ireland

ABSTRACT

This paper describes ongoing work carried out in the context of the DT4GS (Digital Twins for Green Shipping) EU Horizon funded project. In DT4GS, digital twins are utilised in the context of supporting the decarbonization of the shipping sector through new green ship designs and the retrofitting of the existing fleet with green technologies. The digital twin is underpinned by a knowledge graph that connects concepts and instances from heterogeneous ship subsystems with performance parameters pertaining to green shipping technologies and hosts black box (pure data based), grey box and physics-based ship models.

Moreover, interoperability between models and data from different technical domains including cross-domain simulations, and 'what if' scenario analysis is supported.

In this paper we discuss how the knowledge graph supports the intelligent exploration of alternative green ship designs and decarbonisation technologies and their trade offs in terms of emissions, costs, and other relevant technical and socioeconomic parameters.

Keywords: digital twin, green shipping, knowledge graph, cross domain simulation

1 INTRODUCTION

1.1 GREEN SHIPPING

Sustainability is the long term goal of the maritime industry. Global shipping activity emits significant amounts of greenhouse gas emissions and contributes to climate change due to its consumption of fossil fuels. The emissions from international maritime transport are estimated to be around 2-3% of total global greenhouse gas emissions. As a result, emissions regulations are getting stricter, aiming towards reducing the industry's environmental footprint. For instance, the International Maritime Organization (IMO) has mandated that the shipping industry bring down CO2 emissions by 50% by 2050. Several technologies that contribute to the reduction of maritime emissions have been proposed, installed and evaluated over the past years. However the problem of efficient green shipping is a complex one, involving interrelated social, economic and technical considerations.

1.2 KNOWLEDGE GRAPHS

A Knowledge Graph (KG) is a knowledge representation structure that interconnects concepts represented as nodes with semantic relationships that reflect the organisation of knowledge in a particular domain. In fact, the domain represented by a KG can be a superset of diverse domains, thus a KG can model cross domain knowledge. KGs have been used in a multitude of applications, i.e. for modelling social, medical, engineering and other domains. Notably, KGs can be used to model interdisciplinary knowledge and its interdependencies. This makes it suitable for modelling knowledge of complex systems (systems of systems). In this context, a digital twin is the digital representation of a complex system such as a building, factory, aircraft and vessel. KGs provide the underlying infrastructure for realising digital twins.

1.3 Rationale and research objectives

In this paper we utilise knowledge graphs to implement digital twins of ships with the purpose of engineering analysis of green shipping technologies such as hull and propulsion optimisation, new fuels, wind propulsion etc. A KG underpinning a ship digital twin is also a platform for deploying ship subsystem simulations and other engineering analysis tools, in interconnected workflows that allow the end to end analysis, optimisation and impact assessment of a green technology.

The ability of KGs to interconnect heterogeneous domains, makes possible to propagate the effects of an engineering change such as a 'green' modification of a ship's subsystem or component to other subsystems and components belonging to different domains, allowing the estimation of the impact of the proposed change to emissions parameters, while taking into account costs and other relevant business factors. This enables a holistic end-to-end assessment of a proposed retrofitting, towards greener shipping.

Organisation of the paper

The paper is organised as follows. The next section surveys related work in knowledge based ship design, libraries of ship design knowledge and the use of knowledge graphs in ship design and building. Section 3 describes the KG we have developed for the purpose of green shipping engineering analysis, its overall organisation and change propagation algorithm. Section 4 presents a case study of analysis of the impact of engine retrofitting for improving emissions. Finally, Section 5 discusses possible directions for further research.

2 Related Work

2.1 Open Source ship model Libraries

Ship model libraries refers to a collection of objects, which work together to accomplish the required design task. These objects are the tools which the library contains and contain knowledge or perform functions, calculation or operation. Being an open platform allows the library to not be bounded to any proprietary software, which adds freedom and flexibility while developing and integrating different tools. Library models can pertain to early (conceptual) or later (detailed) design activities.

2.2 Knowledge based methods for ship design

Knowledge based methods for ship design link individual design methods techniques and models into a web of knowledge. With knowledge based methods, the integration of ship CAD data with other types of information can be made available to an interdisciplinary team of engineers. The design constructs stored in the knowledge base can be used for context sensitive design. For a given problem only applicable solutions are presented to the user hereby reducing the probability of design errors. Quality control can be achieved with validation of solutions based on the knowledge available. For instance, design agents can use the knowledge model to understand the solutions preferred at a specific shipyard. The standards available can be used for the configuration of the design agent's CAD system.

2.3 knowledge graph for heterogeneous ship model interconnection

knowledge graph modeling techniques and application methods for ship heterogeneous models have been proposed by Dong et al (2022). In the process design and reuse of marine component products, there are a lot of heterogeneous models, causing the problem that the process knowledge and process design experience contained in them are difcult to express and reuse. Therefore, a process knowledge representation model for ship heterogeneous model is proposed in this paper. Firstly, the multi-element process knowledge graph is constructed, and the heterogeneous ship model is described in a unified way. Then, the multi-strategy ontology mapping method is applied, and the semantic expression between the process knowledge graph and the entity model is realized. Finally, by obtaining implicit semantics based on case-based reasoning and checking the similarity of the matching results, the case knowledge reuse is achieved, to achieve rapid design of the process.

2.4 CHANGE PROPAGATION ANALYSIS

Change Propagation Analysis (CPA) describes the set of techniques that analyse how change initiated in one aspect of a design can require knock-on changes to other parts of the design, for the design to work together as a whole (Brahma & Wynn, 2022). The types of connections among the design elements and the type of change influence how change may propagate across the entire design. Additionally, CPA can support the assessment of how a proposed change might impact a design and the generation of alternatives for implementing change, as well as the cost of redesign. Input to CPA models can be represented using a network diagram to specify dependencies between design parameters. Such dependencies can involve constraints as well as informational, energy, mechanical or other flow type dependencies, across multiple domains.

3 ARCHITECTURE OF THE KNOWLEDGE GRAPH

Although the KG is a flat structure, it is conceptually organised as four layers:

The first layer comprises ship subsystems and components, connected with whole-part type of relationships (See figure 1 as an example).

The second layer comprises variables that refer to properties of ship subsystems and components. Links between variables indicate dependencies as spatial, material, energy and/or information constraints (Ma et al, 2003).

The third layer comprises nodes that correspond to models that calculate properties of ship subsystem components such as hull hydrodynamic efficiency, engine efficiency etc. Models implement scientific calculations that use variables from the second layer as inputs and outputs.

The fourth layer implements analysis workflows that consist of end to end model executions and output parameter propagation in order to understand the impact of change to independent variables to dependent variables. Independent variables include goals such as operational requirements, and external conditions (e.g. sea and meteorological) conditions, while dependent variables include performance metrics such as emissions levels. Figure 2 illustrates the concept of change propagation analysis through variables and models interconnected using the KG.

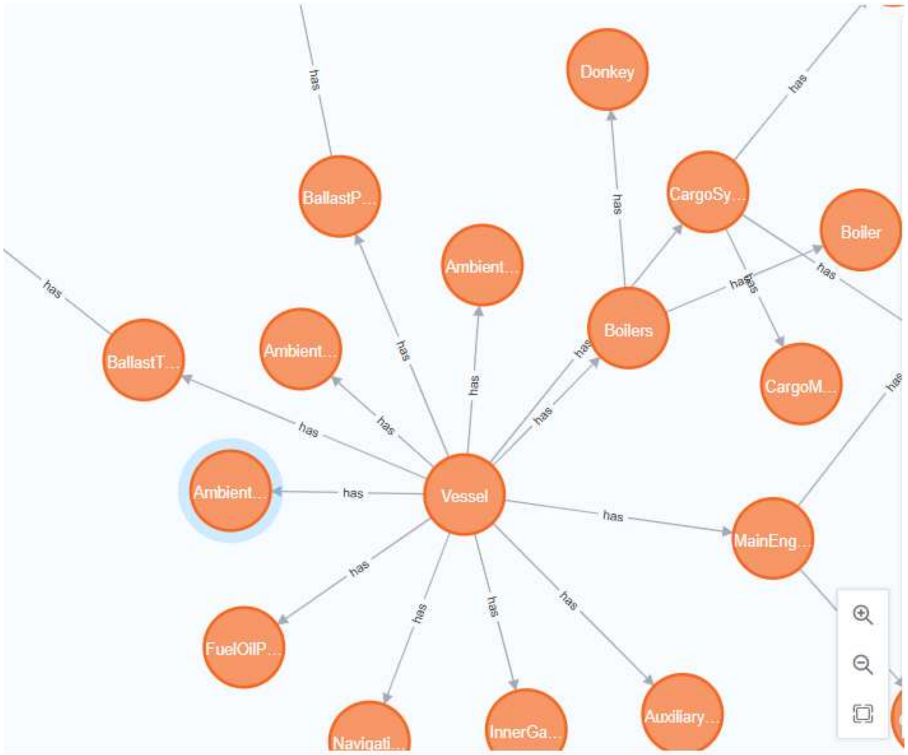

Fig 1. Part of a Knowledge Graph of a vessel and its subsystems.

Table 1 illustrates the KG modelling of ship design and engineering models and their input/output parameters. In Table 1 a model that calculates DG power utilises fuel consumption variable as input and produces a calculation of the engine effective power as output.

Table 1 Model node with input and output variables

Input variable	Model	Output variable
identity: 140, labels: ModelInput properties: name: DG FOC required: 1	identity: 147, labels: ModelInstantiation properties: label: DG power calc model instance	identity: 142, labels: ModelOutput properties: name: Active Power

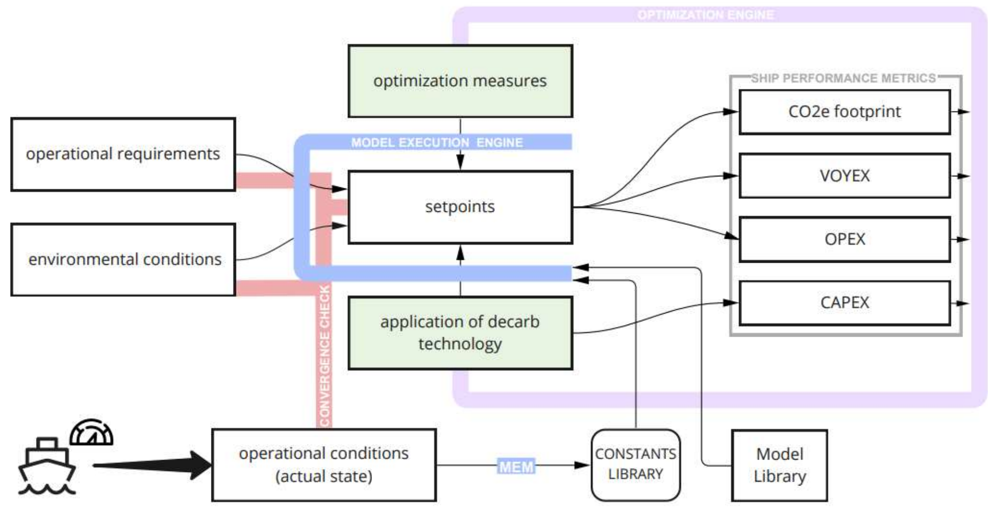

Fig. 2 Illustration of workflow for impact assessment

4 USE CASE: ENGINE RETROFITTING CHANGE ANALYSIS

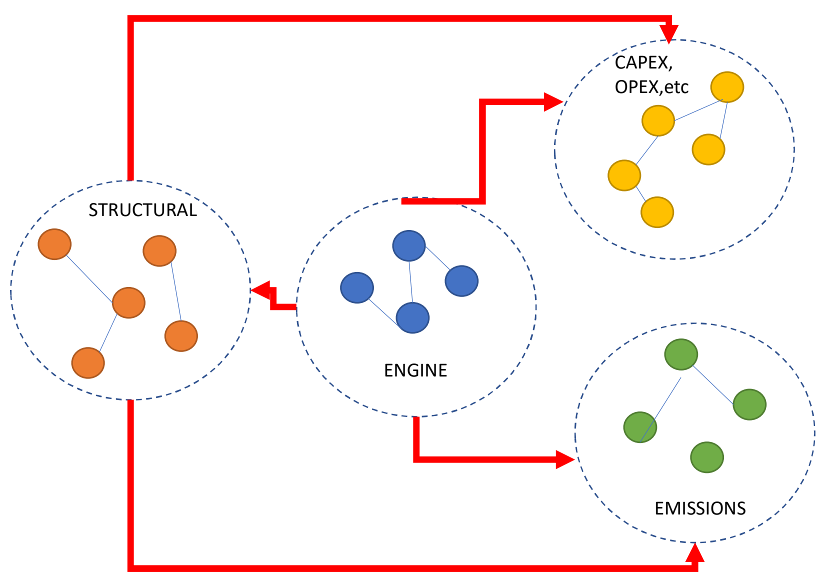

Fig. 3 Impact propagation of engine retrofitting.

In this section we illustrate the application of the KG to the change impact analysis of engine retroffiting with green technologies, more specifically 'greener' fuels such as ethanol and methanol. In general, retrofitting ships with green technologies has as purpose to improve the environmental performance by reducing energy usage and emission levels, without altering the ship service profile (Global forum). At the same time, retrofitting has to be carried out within the constraints of existing hull geometry, compartment division and machinery/equipment/outfit arrangements.

Preparing a vessel for retrofitting may also include design elements such as leaving free space for additional storage and pipe routing, preparing containment systems for zero-emission fuels, carbon capture devices, and structural reinforcement for future loads. ensure that this process was carried out smoothly while integrating and interfacing with the existing systems on the vessel (Wartzilla). Space and appropriate structural reinforcements must be considered for accommodating the retrofit of a containment and fuel supply system. Through this approach, the space for the fuel gas supply system, relevant pipe routing and engines future components must be accommodated in the ship's design.

This analysis is illustrated in Figure 3, where the main knowledge domains and their dependencies are illustrated. So as per Figure 3, engine modifications can create both direct and indirect change propagations to structural components of the system and to emissions parameters. Improvements to emissions via greener fuels for instance may require additional storage space and structural alterations to the vessel. This can however impact its overall energy efficiency as it reduces the cargo storage space. With the assistance of the knowledge graph dependencies, the flows from fuel tanks to the engine and from engine to exhaust system can be analysed and their change impact understood. Auxiliary systems for fuel pressurisation and conditioning, and for engine exhaust collection and processing can create additional requirements for supporting systems, while existing power, space, infrastructure such as piping availability and constraints must be taken into account.

5 Conclusions and further work

Analysts predict that in the next five to ten years, there will be a race towards higher and higher efficiency at the vessel level, and at the system level. To achieve such efficiency, new design tools will be required to support holistic ship design for efficiency, particularly regarding its environmental performance profile. A knowledge graph based approach as presented in this paper supports the holistic optimisation of ships by interlinking knowledge from heterogeneous domains including green technologies, finance and operations.

As part of future research we will continue to improve the practicability of our method: More semantic information will be used to describe the links between the nodes of the knowledge graph. As some dependencies between ship components can be highly complex, fuzzy and probabilistic types of dependencies will be modelled. For instance, Monte-Carlo simulations of the change propagation can be carried out. Graph-theoretic analysis of dependencies as well as constraint satisfaction approaches will also be investigated.

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