Analysis of Economic and Environmental Performance of Retrofits using Simulation

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Abstract

Increasingly ship operators are under pressure to respond to demanding environmental regulations, e.g. ballast water treatment. Often these problems must be solved by some retrofitting activity, like installation of a treatment unit. As most applicable technologies are quite new, a decision is difficult to make. The whole life-cycle must be considered, not just initial investment and operating cost. This requires a detailed analysis of the retrofitting process.

Our approach uses production simulation to determine actual exchanges with the environment and resulting overall cost. The method shall enable stakeholders of retrofitting projects to take an informed decision among implementation alternatives and strategies. It also provides another perspective to judge the feasibility of greening technologies, in particular from an environmental view.

1. Introduction

Environmental operating conditions and effects of marine vessels are currently in the focus of regulating authorities, since the contribution of marine traffic to pollution and other negative impacts on marine life has - at least in some geographical regions - reached levels that have spurred various regulatory activities. Typical examples are topics such as ballast water treatment (BWT) to avoid spreading of marine species to other habitats, or the avoidance of air pollution at sea and coastal regions resulting from engine exhausts.

For many of these issues, counteractions have been or are being devised. In many cases, several options exist for how to address the target issue. For example, pollution caused by exhaust from engines may be reduced by either reducing the exhaust volume as such as a result of improved efficiency and less fuel consumption, or by removing the most problematic polluting substances (like SOx or NOx) from the exhaust fumes. To reduce the total amount of pollutants at least two general philosophies exist: either the level is reduced by cleaning/filtering/neutralizing the exhaust gas or by switching to a completely different type of fuel (e.g. LNG). For the any of these options multiple implementation solutions exist. As can be seen from the exhaust example, some measures may at the same time be combined with a reduction of operating cost. This leads to a complex decision problem for owners and makes it a complex task for consulting entities to provide optimal advice.

As already indicated, there is a strong economic impact related to this topic. While regulations, when ratified and enforced leave no general choice other than implementing a compliant solution, there are also often situations in which the economic conditions are the driving factor. The cost of fuel is again a good example. These kinds of motivations tend to be more complex and sensitive, as there is often more room for variation. It is therefore important to combine economic and environmental aspects when trying to analyse solutions in order to support the decision making process. However, this is leading us to fundamental questions concerning the definition of the environmental and cost impact resulting from the environmental balance of a product’s life cycle. The methodology of ‘Life Cycle Assessment’ (LCA) has been developed to aid in the appraisal of these issues.

2. LCA analysis

Life Cycle Assessment is a methodology applied to evaluate the overall environmental balance of a product or service. A key element of this method is a qualitative and quantitative analysis of products' and/or processes' (services) effects in terms of consumed resources and emitted or disposed substances, energy or radiation (e.g. noise). This analysis is applied to the whole life cycle of a product or performance period of a process under investigation. Covering the whole life cycle is often referred to as the "cradle-to-grave" approach, see Fig.1.

More recently, the methodology has developed to include among its appraisal boundary, the so-called three pillars of sustainability: people, planet, profit, *Guinée (2011)*. The planet aspect, meaning the environmental facet of the study, was the initial trigger in the formation of the methodology; however, it has advanced to include additional and more complex impacts. Similarly, the methodology also encompasses a way to account for the 'profit' pillar; the Life Cycle Costing (LCC) addition strives to include and assess economic factors, along with environmental impacts, throughout the complete life of a product or a service, with the aim of increasing even more the holistic approach of the practice, *Rebitzer and Hunkeler (2003)*.

As mentioned above, the standardised LCA method is a process model assessment, which includes a detailed inventory of resource inputs and environmental outputs (i.e. input and output *flows*), while additionally computing mass and energy balances, and evaluating potential environmental harm. The method, throughout its 'holistic' approach, is capable of serving as an evaluating tool, in order to improve environmental quality and sustainability.

Elementary *flows* are defined as per ISO as "material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation", *ISO (2006)*. This last refers to flows that enter the technosphere (i.e. the system being assessed) from nature, such as resource flows (e.g. iron ore); and flows that leave the technosphere system to nature as emissions, whether they are directed to air, water or soil.

In recent years, the LCA methodology has been applied commonly for two purposes: one using elementary flows and potential environmental impacts in order to account for the history of a product, or a system; and the other which studies the future environmental consequences of a product or a system, versus and alternative.

In either of the two purposes, LCA allows decision makers to study the entire product system instead of focusing on a single process, hence avoiding the potential underestimation of environmental impacts. More specifically, LCA data can identify the transfer of ecological impacts from one environment to the other; for example, eliminating air emissions by creating a wastewater effluent instead. Similarly, it can pinpoint potential impacts shifting from one life cycle stage to another; for example, from use and reuse of the product to the raw material acquisition phase, *SAIC (2006)*. An additional benefit resides in the capability of quantifying environmental releases to air, water and land in relation to each life cycle stage; and that this information can also be tied up to other factors, such as costs and performance data for a relevant product or process.

LCA has grown from a methodology thought and applied strictly to potential environmentally harmful processes, to a tool applied and used to improve product design, while additionally used to enforce product regulations. The use of the methodology has also extended to various different types of industry, finding widespread use, and it is included even among novel management practices, *Rebitzer (2005)*. Because of its ideal application as a design tool, LCA is usually carried out before a product is built or a process is established. It is used among other things to provide additional information during design, which can be used to investigate alternatives and to enable sound reasoning for decisions to be made. The fact that the product is most likely still under design means that LCA has to be performed using a model that reflects the expected properties of the product.

Therefore, the LCA has to be based on models reflecting all essential product or process characteristics.

Unfortunately, the methodology requires intensive data gathering, which could prove expensive and time consuming. Additionally, compiling all material and energy balances for each relevant process is impractical; therefore, the methodology calls for proper boundary setting, in order to assess complete systems. Both, boundary setting and data gathering can influence results certainty, by erroneous adjustment on the first, and lack of availability on the second, for example; both of these issues should be kept in mind by the LCA practitioner in order to avoid erroneous results.

Some of the key challenges when performing an LCA are:

- Capturing the life cycle involves the consideration of a large number of variables that may have an influence. Particularly for one-of-a-kind type products like most maritime vessels the construction period is a resource intense phase that has entirely different characteristics compared to the vessels in-service operations. Decommissioning is also considerably different e.g. from common recycling procedures. Similarly, repair and retrofitting activities involve another set of unique processes.

- Forecasting the performance of the product poses a challenge to identify the key performance factors and drivers. For a typical ship the operational profile mix must be captured and reflected. In this process various assumptions need to be made which typically leads to the definition of multiple scenarios to be evaluated.

- Managing the complexity of the problem is a key factor as well. It is important to introduce reasonable simplifications in an LCA model to control the number of input parameters.

- Determining the relevance of various details is needed when trying to establish a model that involves simplification in order to select the most important factors.

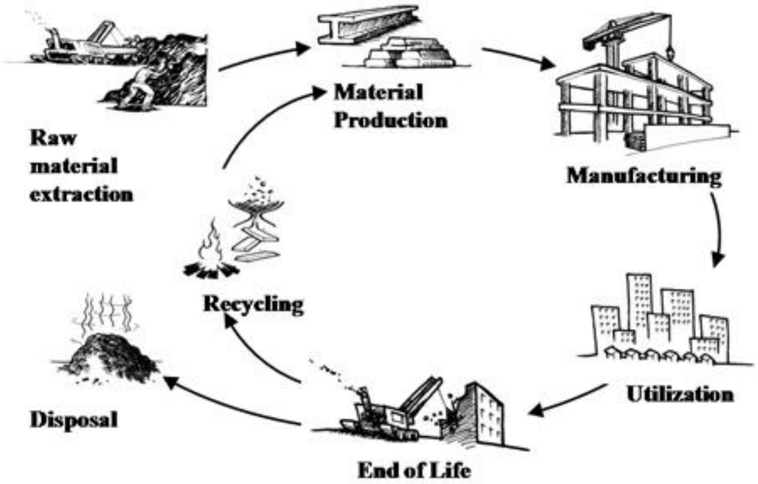


Fig. 1: Product life cycle phases, from *FhG (2012)*

3. Ship Life-Cycle

The life cycle of a ship is characterized by four main phases: planning/ordering, construction, operation/maintenance, and decommissioning/scrapping, *Fet (1998)*. These phases have substantially different economic and environmental profiles; for example, within shipping, the life cycle concept is often understood as the period from when the ship is contracted to hen it is sold. Therefore, when starting to investigate this in more detail, the operation phase turns out to be potentially quite complex. A ship may operate on different trading routes, for example; it may also change ownership, and be in need of regular inspection, maintenance and - due to the long life span - will additionally undergo modifications, retrofits, etc. Moreover, the assessment of its economic life is often focused on its trading profit, *Fet (1998)*, see Fig.2.

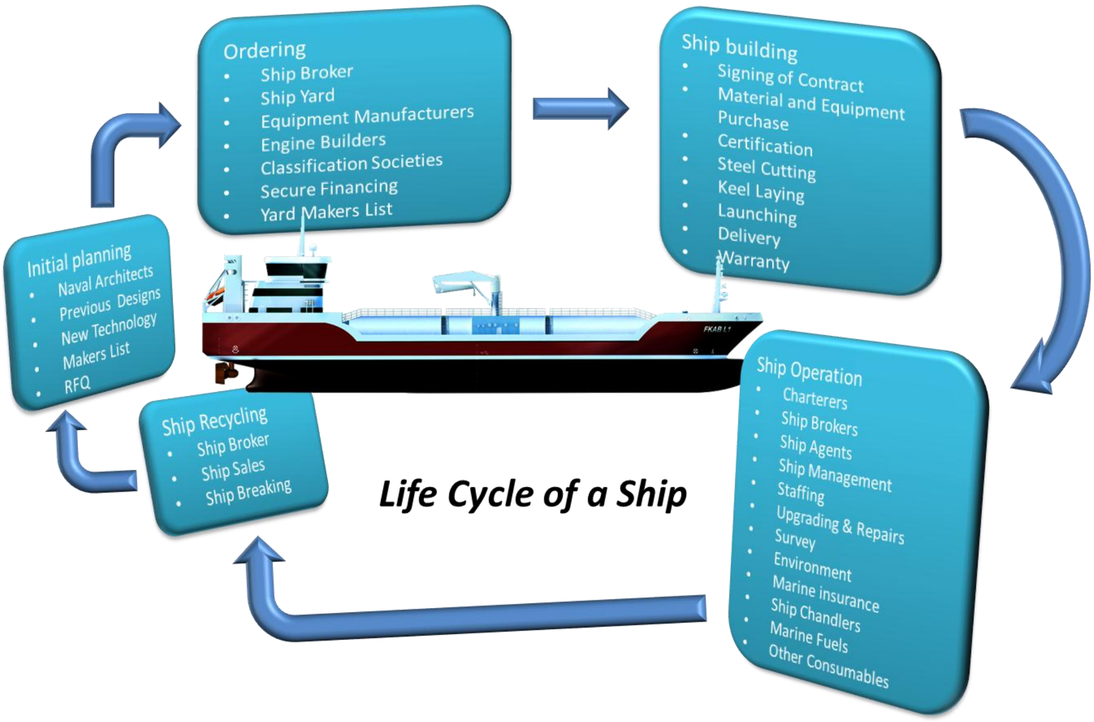


Fig. 2: Life cycle of a ship, from *Ship (2012)*

Furthermore, and mostly during the operational phase, the vessel will produce emissions, generate wastes, and discharge various effluents, which will incur in the contribution of greenhouse effects, acidification, eutrophication, and other environmental impacts, *Fet and Sørgård (1998)*. In the other hand, while contributing at a minor scale, shipyard processes included in the building phase, and scrapping operations, i.e. the end-of-life phase, could also incur in relevant environmental and cost impacts, and therefore should also be included in the assessed vessel’s life span.

It is of importance to gather all available information regarding main construction or repair materials (e.g. ship erection modules, engine blocks, shipboard systems, piping, etc.), as well as energy consumption inputs, throughout the different life cycle phases of the specified vessel, in order to list them as available data inputs for the LCA modelling. The following is a list of minimum expected input information for modelling purposes, as adapted from, *Blanco-Davis and Zhou (2012)*:

- It is beneficial if one is able to choose a specific case vessel scenario (e.g. an existing ship or system in order to model after). If one is able to narrow the broadness of a sample, detailed data can be gathered, which will simplify and provide for a more detailed assessment.
- Gathering of as much general information from the case vessel as possible, in order to complete an operational profile is essential. This will also allow for assumptions and educated guesses when information is not available. The following elements, while not compulsory, could assist for performing more detailed assessments: annual voyages (light/heavy), operational schedule (sea/harbour), bunker price, fuel consumption, cargo volume, etc.
- Modular material composition is also essential for a complete assessment; as well as any type of energy consumption, including water, compressed air, fuel, etc. Disclosed information may

not include all details, specifically material composition and weight information; manufacturers and actual on-board applications may possibly be the best source of information available.

- Information such as purchase, installation and operational costs of the shipboard systems (or retrofit option to be assessed) are very important for comparative assertions between an array of competing or different alternatives. This information allows putting into perspective systems' environmental balances versus economical scores.
- Information regarding transportation and manufacture processes is also beneficial for complete cradle-to-grave assessments. While this information is really difficult to come across to, manufacturing plant and/or shipyard location and purchasing information may allow completing better case assumptions.

Lastly, please note that data related to labour rates, machinery use, and flow (material and energy) costs if available, can be used to comprise a Life Cycle Costing (LCC) assessment, to be performed parallel to the LCA. If this kind of information is not readily available, relevant information to be recorded as mentioned above includes capital and operational expenses, in order to perform a cost-benefit analysis at a later stage, linking environmental scores to these results.

With the specified model created as mentioned above, the user will have a baseline scenario of the environmental impacts produced by the most 'normal' operation of the vessel in question; therefore, using elementary flows and environmental impacts in order to account for the history of the ship, and additionally to extrapolate to potential future impacts. Any alternation in the most common behaviour of the operational profile, e.g. change to low-sulphur fuel, can now be assessed versus the baseline scenario. Secondly, the user can also now compare the baseline scenario with an applied retrofit or maintenance application, in which current and future environmental consequences of each system can be appraised. This in turn offers the simulation end-user extended control over system inputs, and the flexibility to adjust them through various operational profiles, allowing to foresee different applicable alternatives, and aiding in the decision making process of these.

4. From Production Simulation to LCA

Simulation of planned production processes of a ship is used by several shipyards today, and may become a general and relevant part of production preparation planning activities. Therefore it seems logical to try to transfer this technique to retrofit projects. Since these projects are characterised by short planning periods and highly dynamic decision making processes, a powerful validation method like simulation has a promising potential for decision support.

To support LCA analysis through simulation, additional capabilities are needed in the software systems employed. The production simulation system being suggested here has previously been used for shipbuilding production, as described in *Koch (2011)*.

Fig. 3 shows the overall composition of the developed LCA tool suite. Based on existing tools for performing LCA and for executing shipyard production simulation, new functions have been added to implement the required functionality for the retrofitting assessment scenario.

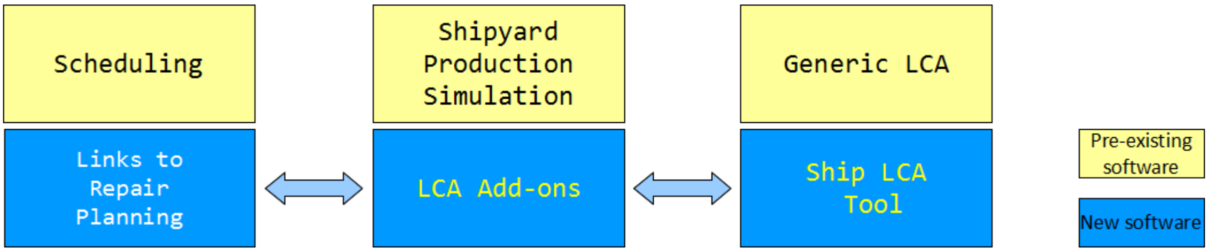


Fig. 3: System architecture

Production simulation is intended to provide better insight into complex production work flows. It uses a model of the production facilities, resources and workloads; possibly combined with a more or less detailed planned schedule, in order to validate the intended production process execution, the execution sequence and dependencies, and the schedule adherence and resource utilization or demand. The actual input and output varies depending on the available information and the questions posed. For example, given a drafted schedule, a simulation may be used to generate its own sequence of events by allowing jobs to start based only on non-schedule related constraints (e.g. availability of material and resources). Relaxing resource constraints would lead to results providing details about the maximum resource demands, while observing other production constraints. Other applications include identification of process bottlenecks, inefficient resource utilization, or investigating 'what-if' scenarios which may be based on a modified production environment, or a modified schedule, etc.

Production simulation includes tracking of a wide range of performance data for all entities included in the simulation model. For example, for a machine the periods of active use can be recorded together with the type of work being done. For purposes of LCA, the idea for the approach described here is to use these capabilities to generate and track similar data for those properties that are needed to perform a detailed LCA, most notably the consumed and emitted flows.

Furthermore, due to the application area in focus, production simulation methods have to be applied to retrofitting activities. Retrofitting can be characterised as a combination of activities similar to the production of new product components and those typically found in repair. Many repair activities differ substantially from production activities: they mostly occur on-site (thus being somewhat similar to on-board outfitting tasks), and they also include various kinds of "destructive" or removal-type operations like waste disposal, cleaning, removal of damaged/old parts or equipment, performing replacements or removing and reinstalling items for refurbishment.

For the work described in this paper, an initial activity has been to identify what needed to be added or changed for a production simulation system, to be able to apply it to retrofitting activities and whether this could be accomplished in a feasible way.

The main differences in requirements can be summarized as:

- Repair work is usually completely controlled and managed by schedule. This is mainly due to the fact that typical maintenance activities are service oriented, i.e. they often do not follow the typical pattern found in production tasks, where a bill of material is used as input to produce some interim or final product, which is then used in follow-on tasks that depend on the availability of such interim products. Repair tasks in contrast do have logical constraints, but most time there is no relevant material flow between them.
- Retrofitting and modifications can constitute a mix of repair and production tasks. There is often a limited number of part/assembly oriented production tasks.
- Support for task types that are often neglected in production simulations like cleaning, ventilation, installation and removal of access paths, temporary setup of support structures and waste removal and disposal. Some task types need more detailed consideration like painting and surface treatment than is typically applied in new-building production scenarios, for example.
- To provide the desired information for LCA, tracking of LCA flow data is needed. This requires a considerable number of flow parameters for all machinery and facilities being used. The LCA flow data encompasses any kind of relevant flow of substances, energy or radiation consumed by or emitted from any active component being involved in a process. Table I and Table II show a set of sample properties that are applicable to common shipyard production activities, and that are additionally of general interest for LCA analysis.

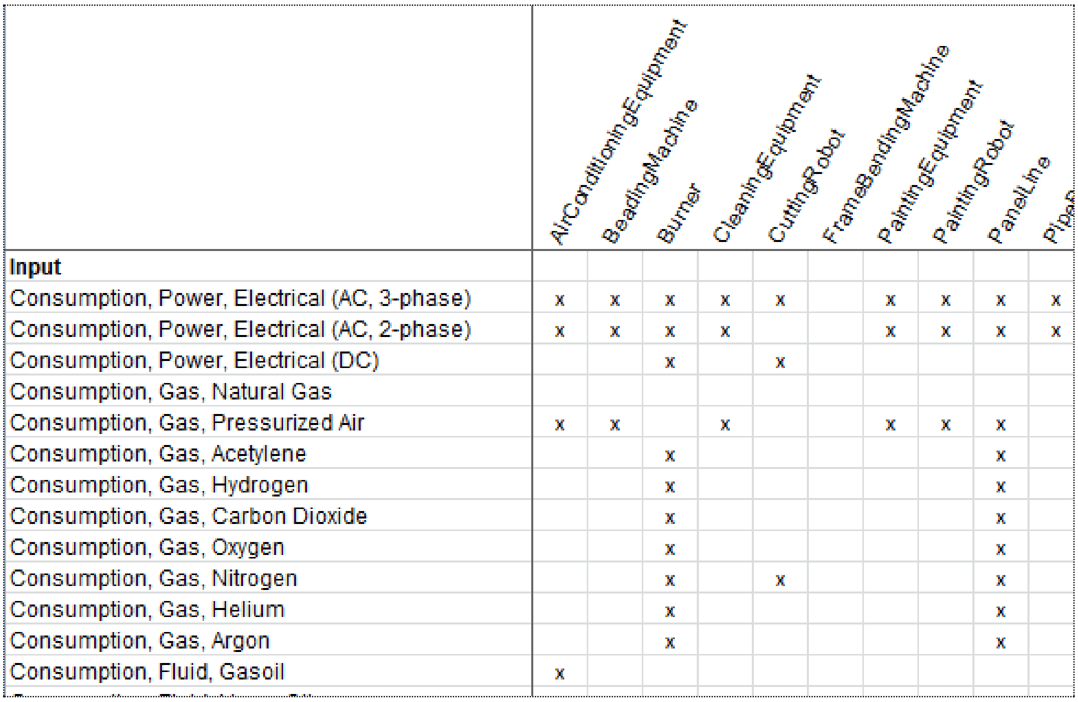
Table I: Sample LCA Consumption Parameters

Parameter	Quantity
Power , Electrical (Alternating, 3-phase)	Energy
Power , Electrical (Alternating, 2-phase)	Energy
Power , Electrical (Direct Current)	Energy
Gas, Natural Gas	Mass
Gas, Pressurized Air	Mass
Gas, Acetylene	Mass
Gas, Hydrogen	Mass
Gas, Carbon Dioxide	Mass

Table II: Sample LCA Emission Parameters

Parameter	Quantity
Water Vapour	Mass
Gas, Carbon Dioxide	Mass
Gas, Ozone	Mass
Gas, Sulphur Dioxide	Mass
Gas, Nitrogen Oxides	Mass
Gas, Chlorine	Mass
Gas, Carbon Monoxide	Mass
Gas, Fluorine	Mass

LCA flows are handled as user-configurable attributes that are linked to production equipment, see Table I and Table II. All flows can be specified as rates (i.e. consumption per hour) or as levels of emission (e.g. noise, vibration). To configure the system, cross tables are used to assign parameters to equipment types. Once this configuration is complete, the user of the system can define specific consumption or emission rates for any of the applicable parameters, while also defining the details of a specific production equipment item. During simulation, these rates will be used to calculate actual prorated and accumulated values. The configuration can be done by using a simple spread sheet workbook as input, and can thus be easily modified and adjusted as shown in Fig. 4.



Input	AirConditioningEquipment	BeadingMachine	Burner	CleaningEquipment	CuttingRobot	FrameBendingMachine	PaintingEquipment	PaintingRobot	PanelLine	Pipe
Consumption, Power, Electrical (AC, 3-phase)	x	x	x	x	x		x	x	x	x
Consumption, Power, Electrical (AC, 2-phase)	x	x	x	x			x	x	x	x
Consumption, Power, Electrical (DC)			x		x					
Consumption, Gas, Natural Gas										
Consumption, Gas, Pressurized Air	x	x		x			x	x	x	
Consumption, Gas, Acetylene			x						x	
Consumption, Gas, Hydrogen			x						x	
Consumption, Gas, Carbon Dioxide			x						x	
Consumption, Gas, Oxygen			x						x	
Consumption, Gas, Nitrogen			x		x				x	
Consumption, Gas, Helium			x						x	
Consumption, Gas, Argon			x						x	
Consumption, Fluid, Gasoil	x									

Fig. 4: Equipment/LCA flow cross table

Once LCA flow data is defined, the simulation system can provide tracking data for any of these parameters. In this context, it is also important to note that the underlying system is capable of describing and maintaining multiple states for any given piece of equipment. The simplest (and default) case would be an ON and an OFF state, which corresponds to all flows pertaining to that machine to be zero or the defined maximum rate. However, frequently used machines do operate in one of several active states. By being able to define flow rates for every state separately, per-task operating conditions will be reflected in the tracked data. Furthermore, it is possible to specify any equipment parameter either as a constant value, a stochastic distribution, tabular data (from which actual data points will be interpolated), or functions that may be defined based on other model parameters.

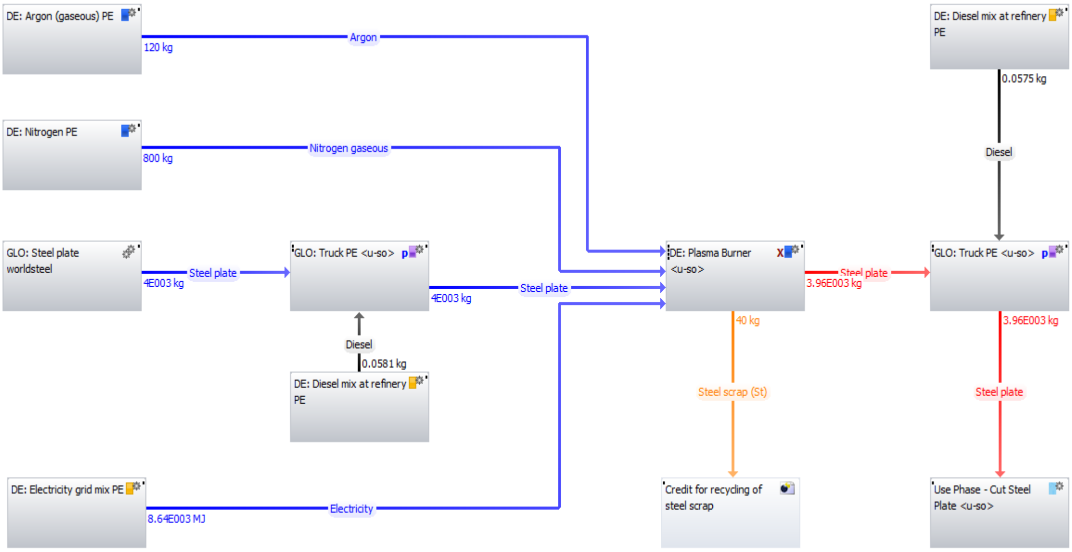


Fig. 5: Sample plasma burner process LCA model, generated with *GaBi (2012)*

Tracked data for any of these process parameters can then be interfaced to corresponding LCA models, 'dragging' specific consumption and emission values from the applied simulation into the LCA. These rates or values are then linked to specified model flows, allowing the LCA software to track all material, energy, and emission inputs and outputs, and allowing it to later analyse, summarise and distribute the results to various environmental impact categories. Fig. 5 shows a simplified LCA model of a typical shipyard process, which is represented as a flow diagram comprised of processes and flows. The basic processes are defined as to include linked results from the simulation.

5. LCA enabled simulation

To perform a simulation of a retrofitting project, a simulation model has to be established. Fig. 6 shows the required input and work flow to prepare, execute and evaluate for a simulation.

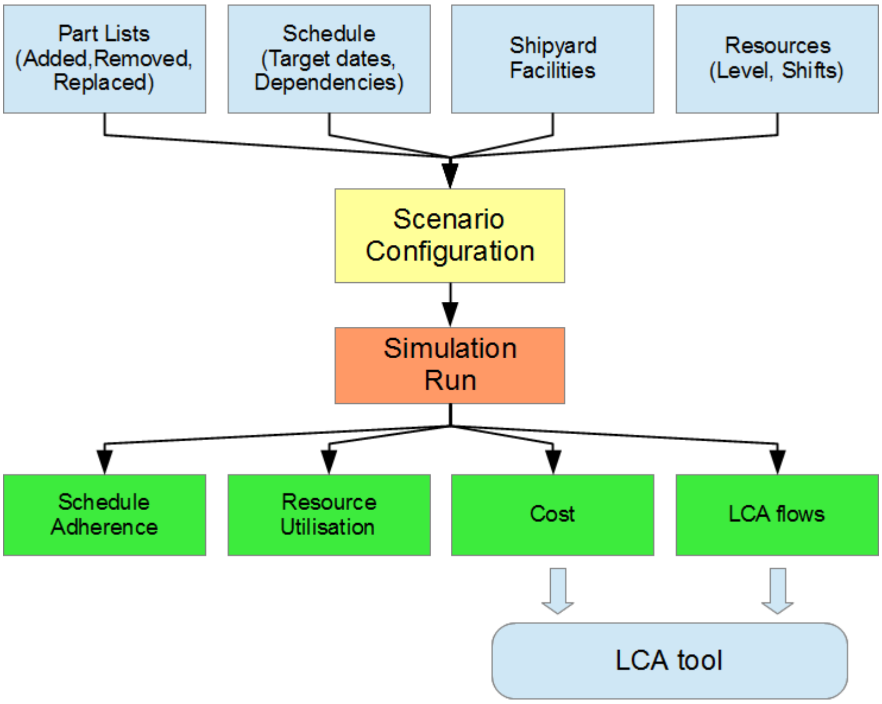


Fig. 6: Simulation work flow

Some parts of this model are fairly static, while others need to be defined for each individual project. To prepare for retrofit simulations, the following initial setup steps are needed:

- Configuration of the LCA flows for all resources involved. This follows the principle as described in Section 4.
- Establishing a model of the shipyard and its facilities. This is a one-time activity, which will only require small scale modifications in due course when shipyard installations are upgraded or reconfigured. The model includes definition of facilities and equipment available for production, retrofitting or repair activities, and will be defined including their LCA flow parameters. Fig. 7 depicts an example layout of a shipyard with buildings and facilities shown in an aerial view on top of a map backdrop. The correct geographical arrangement allows precise definition of transport paths, for cases where the transport activities need to be included in the simulation.
- Definition of LCA flow data is essential for being able to use simulation results in a life cycle assessment activity. Gathering detailed data of this kind can be challenging. First logical sources of information are equipment data sheets, which will often provide at least fundamental data like power consumption. Fortunately, various additional information sources exist - like the *ecoinvent* database, *Frischknecht (2005).* These LCA-oriented

databases provide fairly complete data sets about flows pertaining to a broad range of industrial processes. The information can be directly transferred into the simulation model; in fact, a future development of the system may include direct online access to such data. As part of our development project a direct connection to the ERLCA-DB (Eco-REFITec LCA-Database) is being developed in parallel, *Fercu (2012)*. Fig. 8 shows an example of an equipment definition that includes some LCA flow rates.

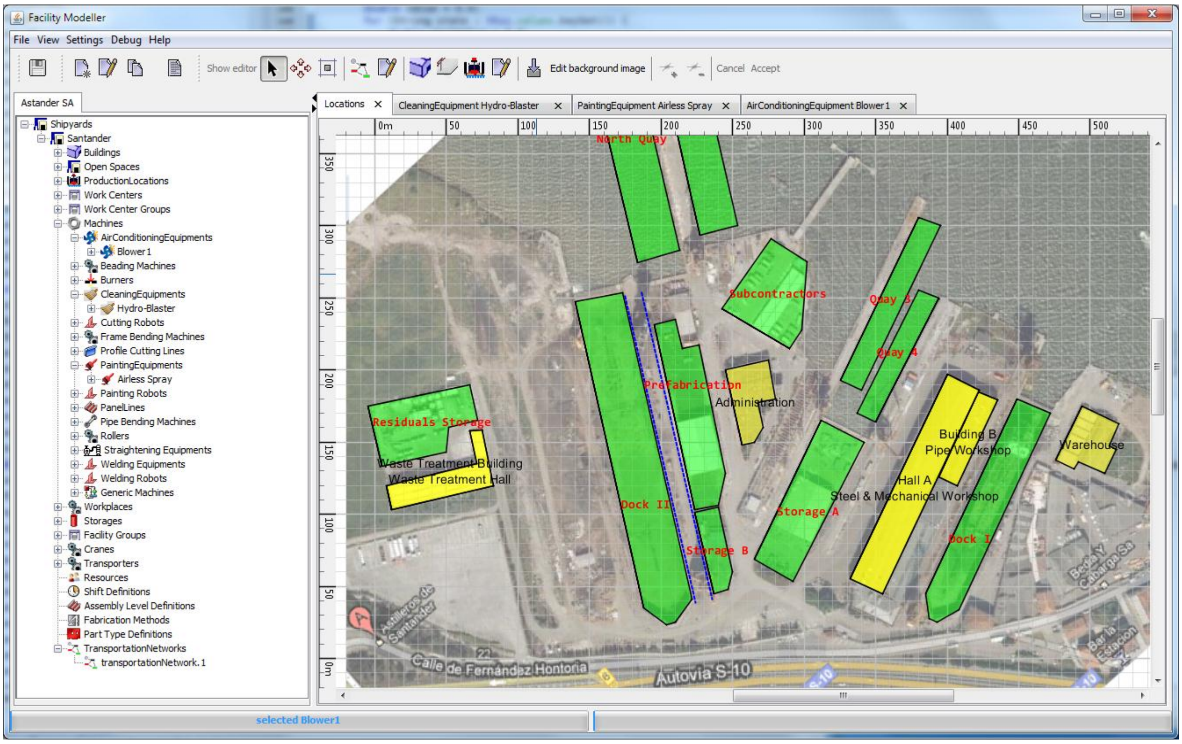
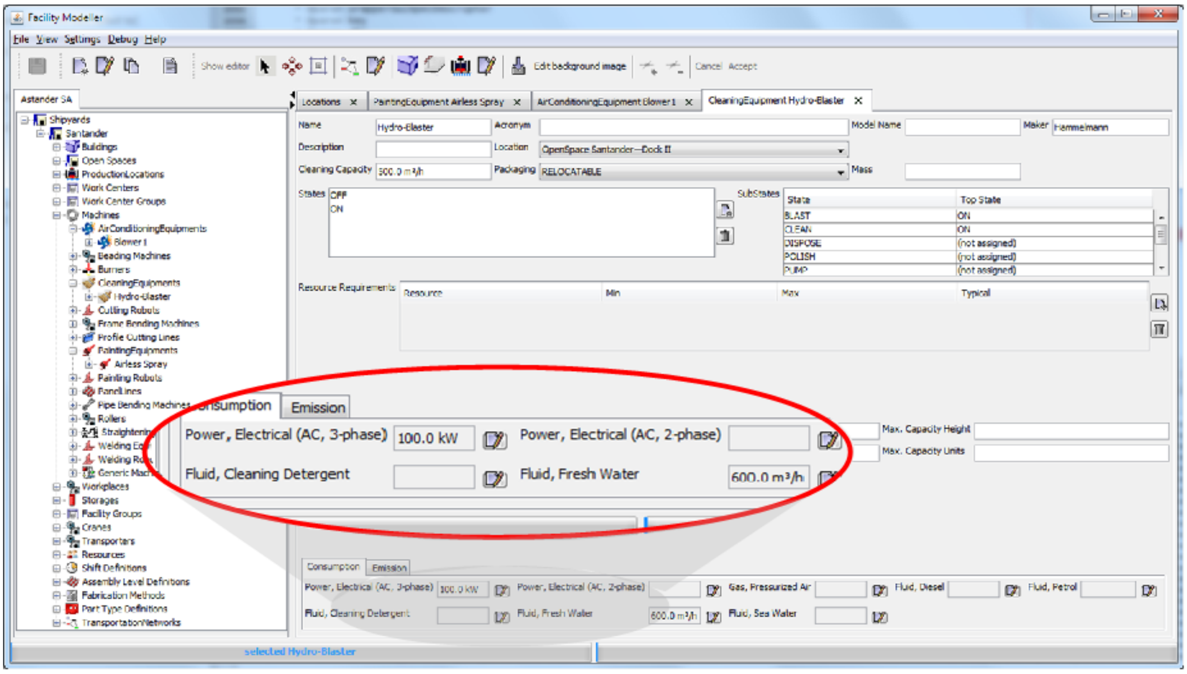


Fig. 7: Shipyard model in a geographic view



Name: Hydro-Blaster
Location: OpenSpace Santander—Dock II
Cleaning Capacity: 300.0 m³/h
Packaging: RELOCATABLE
Maker: Hammelmann
States: OFF, ON

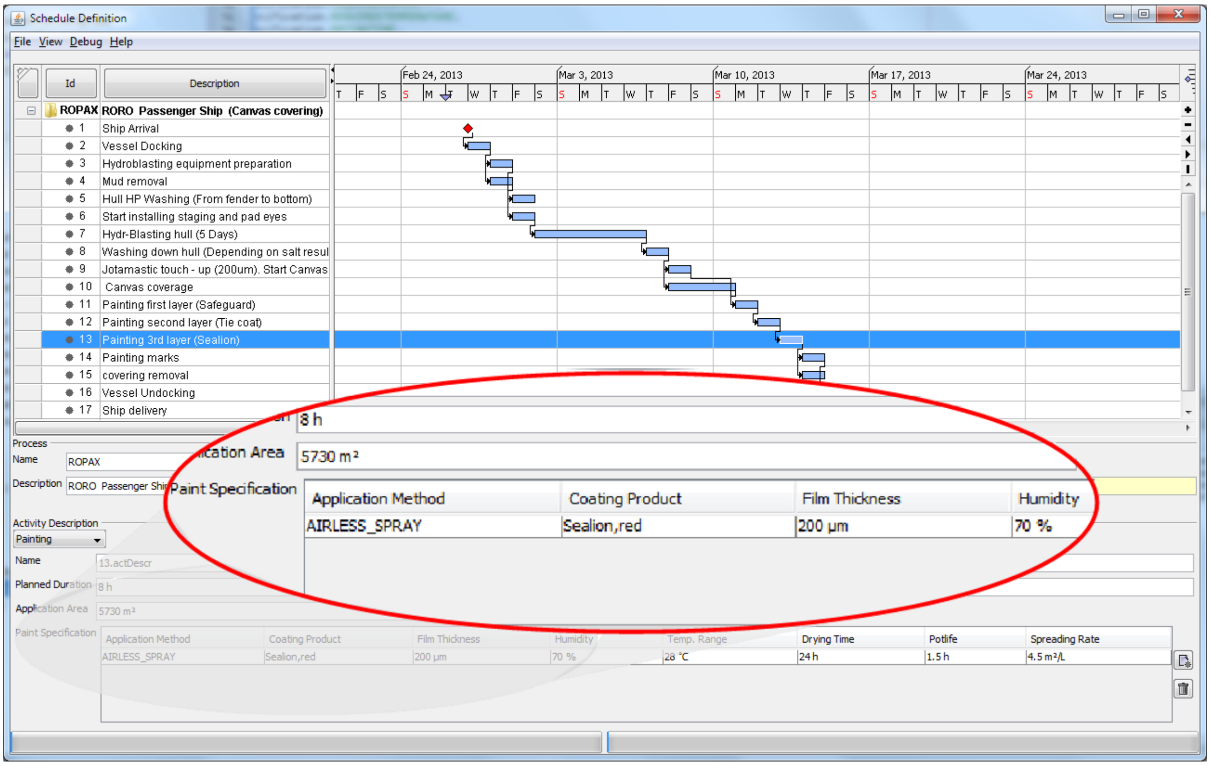
State	Top State
BLAST	ON
CLEAN	ON
DISPOSE	(not assigned)
POLISH	(not assigned)
PUMP	(not assigned)

Power, Electrical (AC, 3-phase): 100.0 kW
Power, Electrical (AC, 2-phase):
Fluid, Cleaning Detergent:
Fluid, Fresh Water: 600.0 m³/h

Fig. 8: Sample facility flow rate definition

Once the shipyard model has been created, individual retrofitting projects can be prepared for simulation. For each project the following actions need to be carried out:

- Modification/addition of equipment that is temporarily used for purposes of the project, e.g. rented equipment.
- Definition of the intended retrofit schedule: it may be imported from an existing scheduling or planning system like MS Project, or it may be created in the scheduling definition component of the system. As part of the schedule definition, some details are required to specify the work content of the individual tasks. For retrofitting activities this is usually straightforward, since this information is directly available for the project specification or offer description documents. Fig. 9 shows an example of an *activity description* that incorporates details about the task to be simulated – in this case a painting specification.



Id	Description
ROPAX	**RORO Passenger Ship (Canvas covering)**
1	Ship Arrival
2	Vessel Docking
3	Hydroblasting equipment preparation
4	Mud removal
5	Hull HP Washing (From fender to bottom)
6	Start installing staging and pad eyes
7	Hydr-Blasting hull (5 Days)
8	Washing down hull (Depending on salt resul
9	Jotamastic touch - up (200um). Start Canvas
10	Canvas coverage
11	Painting first layer (Safeguard)
12	Painting second layer (Tie coat)
13	Painting 3rd layer (Sealion)
14	Painting marks
15	covering removal
16	Vessel Undocking
17	Ship delivery

Process
Name: ROPAX
Description: RORO Passenger Shi

Activity Description: Painting
Name: 13.actDescr
Planned Duration: 8 h
Application Area: 5730 m²

Paint Specification

Application Method	Coating Product	Film Thickness	Humidity	Temp. Range	Drying Time	Potlife	Spreading Rate
AIRLESS_SPRAY	Sealion,red	200 µm	70 %	28 °C	24 h	1.5 h	4.5 m²/L

Fig. 9: Sample schedule definition

- Applicable shift definitions: used to model the availability of resources. Shift schedule definitions are applicable to selected work places and work stations or resource pools to operate in an area or group of facilities.
- Definition of all required material resources: in case of the installation of new components, the replacement of existing components or addition/modification of the ship structure, the corresponding bill of material needs to be imported or defined. This can be used to control the effects of the supply chain, e.g. by specified expected availability, probability of delays, etc. If this is not in focus, instant availability can be assumed instead.
- Setting of simulation parameters: to carry out the actual simulation run, a scenario needs to be defined, enumerating all model components to be included, the stimuli being used to initiate the simulation, and any further controlling parameters. Such parameters typically include data such as the simulated start date, and whether various resource limits shall be applied. The selection of the model entities available aid in the configuration and control the simulation goals.
- Execution of simulation: this is obviously the key step to calculate results. The model will be loaded and the simulation carried out by starting the simulation engine. The actual execution

times depend on the complexity of the problem being investigated. For typical retrofitting cases, this has shown to be negligible. All results are stored in a database for further evaluation.

- Preparation of reports, analysis of results: evaluation can be carried out instantly. Any tracked parameter (including those related to LCA flows) can be selected and visualised or tabulated in various ways.
- Transfer of flow data into the Ship LCA software: once the simulation results have been reviewed, all LCA flow data can be transferred to the ship LCA tool.

6. Sample cases

The system is being applied to several use cases to evaluate the best option for carrying the intended work. Some samples include:

- Application of a new paint system to the underwater hull surface to reduce resistance and consequentially fuel consumption.
- Comparative study of innovative abrasive processes being used for cleaning the underwater hull surface.
- Installation of a ballast water treatment system. This includes comparison of the retrofitting requirements of the different systems being offered.
- Installation of an exhaust SOx scrubber system.

Fig. 10 shows some sample results from the simulation being carried out for the paint system case, including a high pressure water blasting process being applied during the cleaning. The sampled data include overall power consumption, as well as fresh water consumption, which is one of the “hidden” factors for this case.

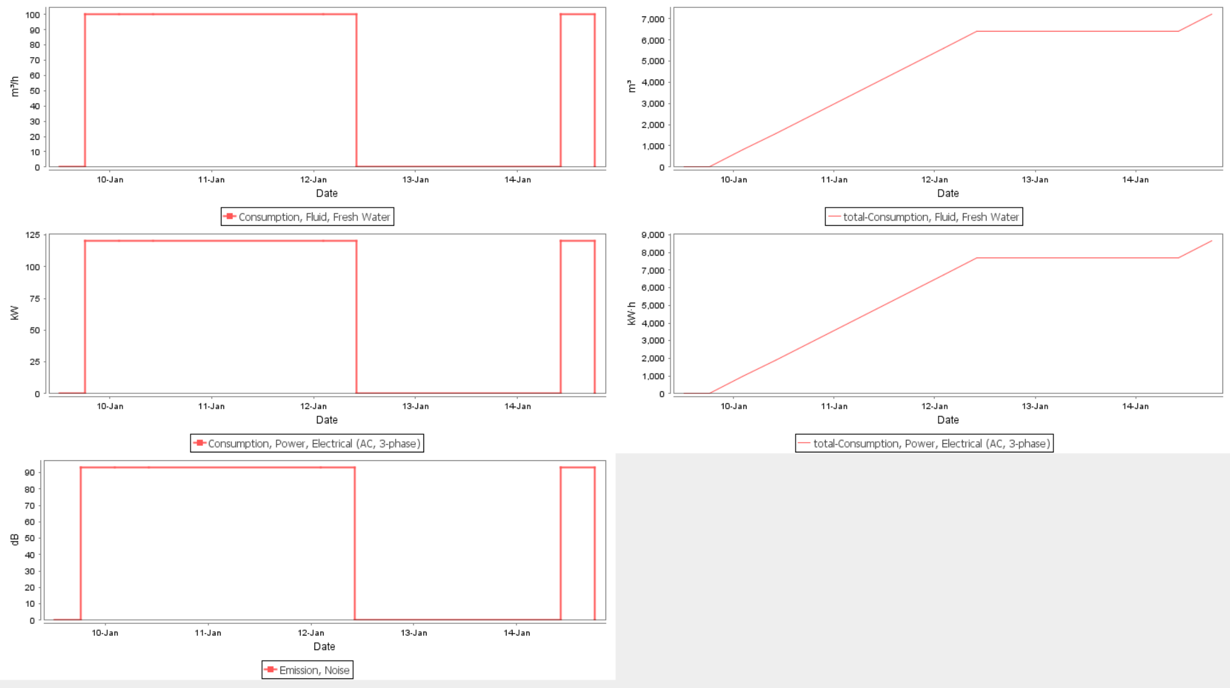


Fig. 10: Sample operating data and LCA flow results

7. Conclusions

A novel application of simulation to the area of retrofitting has been herein proposed. At the same time, features to generate simulation results that can be directly fed into a life cycle assessment task have been introduced. An important feature is that the simulation will be carried out for a specific shipyard setup and an individual retrofitting schedule, such that all influencing factors will be considered. This is very helpful when trying to decide ahead a planned project. This last applies to eco-innovative projects such as the installation of ballast water treatment systems, exhaust scrubbing systems, or propulsion energy reduction techniques, in which many details will depend on the actual ship, the shipyard, and/or the system being chosen, and will ultimately drive the decision.

Input to the system is straightforward, as it is completely based on the available schedule and job specification data. LCA flow rate data input is one of the more demanding activities; however, these are shown to be supported by utilising existing LCA databases.

LCA model generation and appraisal, allows for the computing of historical and forecasted potential environmental impacts, with the possibility of also linking these results to economic factors. This in turn offers decision makers a *holistic* evaluation of a specific option or model (e.g. a specific case ship), or of an array of different alternatives (e.g. different ballast water treatment systems).

A common concern with simulation projects is the effort to establish a validated model, with sufficient level of detail. It has been demonstrated that with a well-adjusted suite of tools, this issue can be very well mitigated. Furthermore, in the retrofitting domain the required shipyard model is of reduced complexity compared to new-building projects, and it only needs to be set up once for a shipyard. Minor modifications are added on demand, like for rental equipment that is temporarily used. The reduced model generation effort paves the way towards comparative studies and hypothetical what-if analyses, which ultimately expand decision space.

Output from the system includes information about production data (utilisation, schedule, resources and cost), as well as LCA flow data that can be used directly in the long-term product LCA, to assess feasibility of a planned retrofitting measure.

8. Acknowledgements

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