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Model-based topology analysis for environmentally conscious power plant operation

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Abstract

Plant operation is tightly linked with plant topology. Each operation task is executed in one or more structure units, which might be associated with negative environmental impacts. In order to design and manage environmentally conscious plant operation it is essential to provide systematic mechanism to model plant topology with respect to environmental measures. The selection of plant topology to perform certain operation requires understanding and evaluation of life cycle activities. In this research, model-based topology analysis is proposed and used to evaluate different operation scenarios in view of life cycle assessment and applied on a case study thermal power plant.
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Keywords: Plant topology analyzer; LCA; CAPE-ModE; POOM; Power plant operation

1. Introduction

Plant topology is represented by structure units and the connections among them [1–5]. It has external elements such as the surrounding environment and internal elements such as sub-assemblies and materials [3,5]. Phenomena occur in structure units as a result of sequence of operation tasks [1,3,4]. Such phenomena represent the behavior of a system and its components. Understanding the structural model of the underlying plant is important to understand, design, and execute the desired operation and to obtain the most suitable behaviors. Plant structural model can be viewed as set of structure units along with their connectivity. In engineering practices, the connectivity is commonly called plant topology. Plant topology can be modeled, i.e. abstracted, in a way that simplifies the real plant topology, which is essential for the analysis, design, and operation of the underlying plant. Process modeling will enable the proper judgment and selection of the most advantageous topology for a given operation. There are many attempts that tried to provide systematic modeling methodology for formal representation of plant topology as linked with other process design model elements. ANSI/ISA-S88 [6] showed that plant operation is mapped to plant structure hierarchies. Such mapping is important for plant control and operation design. In addition it is used as a basis for the design of intelligent computer-aided design and manufacturing execution systems. There are several options and scenarios to achieve optimum plant operation. This requires robust mechanism to evaluate these scenarios with the considerations of life cycle activities. There are several proposals for operation design such as AOPS and CAPE-Oper [7–9] and iTOPS [10], and others. Most of these solutions are based on structuring and evaluating operating procedures in view of structure availability, time, and cost. In this research, and in addition to the previously mentioned topology selection measures, life cycle activities are used to evaluate the selection of plant topology for a given operation. Section 2 shows comparative study of the different process modeling methodologies presented in the domain of chemical process engineering.

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2. Proposed process modeling methodology

Chemical process is quite complex, where it involves different views. It has been referred as physico-chemical process where there is a link between chemical phenomena and the physical systems and structures. Process modeling is used to analyze and design chemical processes. Lind reported multi-flow functional modeling methodology (MFM) which is based on functional modeling of the underlying system and link all system components to their functions [11,12]. Such approach is applied on the design of operating procedures as well as for plant fault diagnosis. There are further developments of MFM modeling methodology by Larsson [13] and Gofuku and Lind [14] where knowledgebase is developed with computer-aided tools to apply MFM on different engineering applications such as operation design, operator support, and alarm and control design. Hybrid Phenomena Theory, HPT, is another process modeling methodology where it enabled the formal representation of the dynamics of the different behaviors. In this regard, Marquardt and his group in Aachen University developed a systematic way to generate system behavior equation models for different phenomena based on mathematical basic models [2]. To overcome model complexities and reuse, Linninger proposed the use of meta modeling which is used to represent process phenomena that occurs in process systems [4]. These process modeling methodologies are realized in computer-aided process engineering tools that are developed and utilized to support product/process design. Another process modeling method was proposed by Lu, who identified the need of separating structure, behavior, and management views of process models to be able to support process systems engineering practices [15,16]. This fact has been agreed by almost all researchers where it was noticed that phenomena could occur in any structure unit based on the selected operation. For example, reaction might occur in the pipe connected to the reactor, rather than occurring in the reactor itself due to abnormal process condition and/or operating procedures, or recipe. Most of the reported difficulties in process modeling, such as model reuse, systematization, domain knowledge, and standard model representation, were eased by the use of object-oriented approach [5,17]. The concept of object-oriented modeling was widely used as a base to construct and formalize chemical process models. Pohjola proposed PSSP, or purpose, structure, state, and performance, which provided basic building blocks of process models. This approach has been further developed using PSSP language and computer-aided tools to design environmental conscious, safe, and waste management processes and products. In addition to process modeling, integrated process and product modeling practices are also proposed by many researchers, for example Ref. [18].

There were further works that have been made in the area of hierarchical structure modeling and production process modeling where process models are linked with production models (i.e. manufacturing execution systems MES). In fact, most of the above mentioned modeling methodologies are applied and/or extended successfully to cover production process models, taking into considerations environmental assessment, risk management [19], and process safety, for example PSSP [3]. POOM or plant process object-oriented modeling methodology, was proposed to systematically model physico-chemical processes and to support the decision making associated with process design and operation, with the considerations of life cycle activities. POOM is based on constructing static, dynamic, and operational models that integrate engineering requirements that support the different life cycle activities [5,7]. POOM is based on the fundamental concepts of object-oriented modeling approach, which was represented using unified modeling language UML [5,20].

The proposed modeling methodology was revised several times to incorporate process design features captured while practicing different case studies of batch, continuous, and discrete plants. In addition, it was applied on production and supply chain processes, such as biomass, plastic, as well as energy and natural resources recycling [5,7,20]. From the author observations, there are key features that are needed to ensure robust process modeling. First is the separation between structure elements, behavior, and operation models. Operation is a set of actions that enables desired behaviors to take place in one or more topology areas. Behavior models can be represented as a set of states and transitions among the different states with respect to process conditions and control rules. Operation models are represented as a set of allowed methods for each structure unit, which simply receive messages from the control system, operator, or external systems based on the underlying structure unit. Fig. 1 shows the basic structure of the proposed process modeling methodology, POOM.

The revised version of POOM shows three basic dimensions. The static dimension, which includes facility, materials/products, topology, and human. In other word it includes static elements of the underlying process. The dynamic dimension includes behavior models, which are represented as states, transitions, and messages. The operation dimension includes purposes and methods to be executed as a response to incoming message. These three main views are the base of the traditional object-oriented modeling approach and can be used to model both process (i.e. controlled) and control system (i.e. controller), as shown in Fig. 2. The complete model can be formalized as

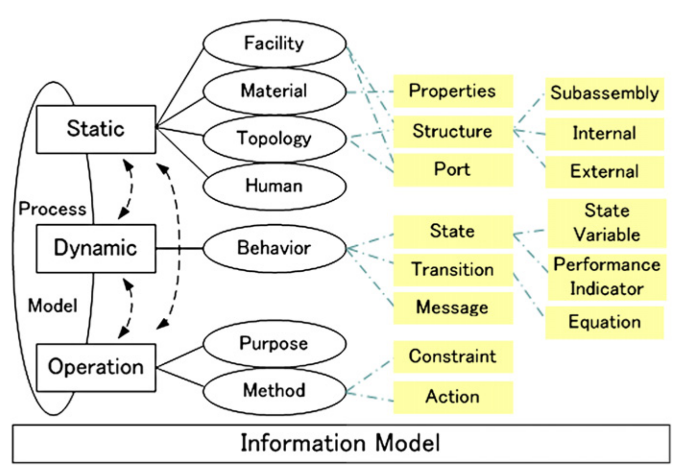

Fig. 1. Process modeling methodology: POOM.

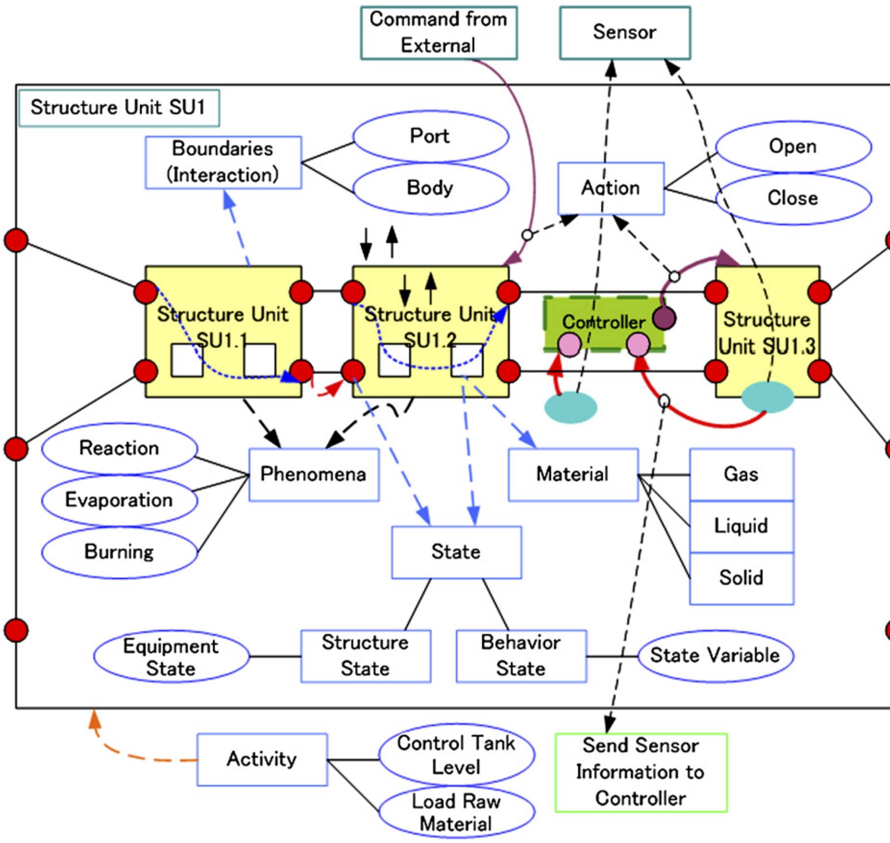

Fig. 2. Example of chemical process model using POOM.

building blocks of static model elements; each is associated with operation and behavior model elements.

Chemical process topology is described in terms of structure units connected through ports. Behavior is described and associated with structure units as per the intended, planned, or actual operation. For example in structure unit SU1.1, there are three behaviors occurred: reaction, evaporation, and burning. Controller is placed within structure unit SU1 where real time information is transferred from the sensor associated with structure unit SU1.3 and another sensor in the internals of structure unit SU1. Based on sensor information and predefined control rules/logic, control instructions are sent to structure unit SU1.3, for example open port or select a certain behavior. Materials are moving within chemical process where they are transformed into other materials or different states, or simply transferred from one place to another. These are the basic three material actions: (1) transformation, (2) transportation and (3) stocking in the same place over time. Control instructions might come also from external entities such as controllers of higher structure unit, or operator, or external system.

In view of the proposed process modeling methodology, POOM, Section 3 explains the proposed topology analysis mechanism.

3. Topology analysis for power plants

In order to explain the proposed topology analysis technique a case study of thermal power plant is used.

3.1. Thermal power plant topology model

Typical power plants can be viewed as shown in Fig. 3. Thermal power plant is fueled via coal, oil, LNG, or LPG.

Fuel is fed into boiler, which includes hot water. Ventilation of boiler is done through ventilation machine. Steam produced from boiler is fed into turbine where electricity is generated via dynamo and transferred to electricity grid via power transmission lines. Based on the heating of fuel in boiler, there are output wastes, which include NO_x, SO_x, dust, and CO_2. These undesired gases are removed through removal equipment, except CO_2, which is removed in the burning tower. Typical thermal power plants are operated using coal, or oil. However, the described power plant includes three possible fuel options that can be used alternatively. In Section 3.2 the proposed topology analysis is explained using the selected thermal power plant as a case study.

3.2. Proposed POOM-based topology hierarchy

As described by ANSI/ISA-S88 [6], plant structure is mapped to show plant operation in hierarchical manner. More details about plant structure–operation hierarchy mapping is shown in Fig. 4.

OIA, or operation isolation area, is defined as the topology area required for a certain operation or maintenance task and surrounded by flow control devices (such as valve, pump, etc.). EIA, or equipment isolation area, is defined as

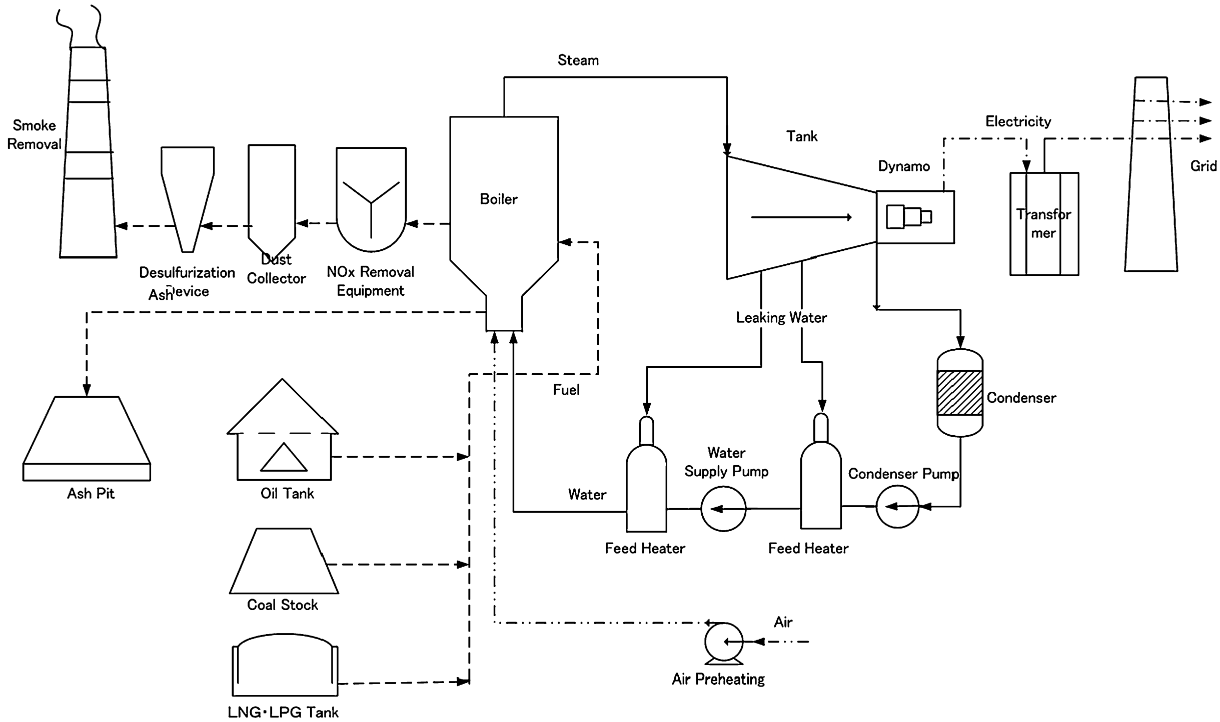

Fig. 3. Example P&ID of thermal power plant.

the topology area around a given process equipment (such as reactor or furnace) surrounded by control devices. JIA, or job isolation area, is the topology area required for a job to take place. Job is set of tasks required to produce product(s), which can be defined in terms of unit procedure or operation tasks. The proposed mapping between structure layers and operation hierarchies starts from the whole supply chain, which consists of group of enterprises. Each enterprise consists of set of sites. Each site might include set of plants.

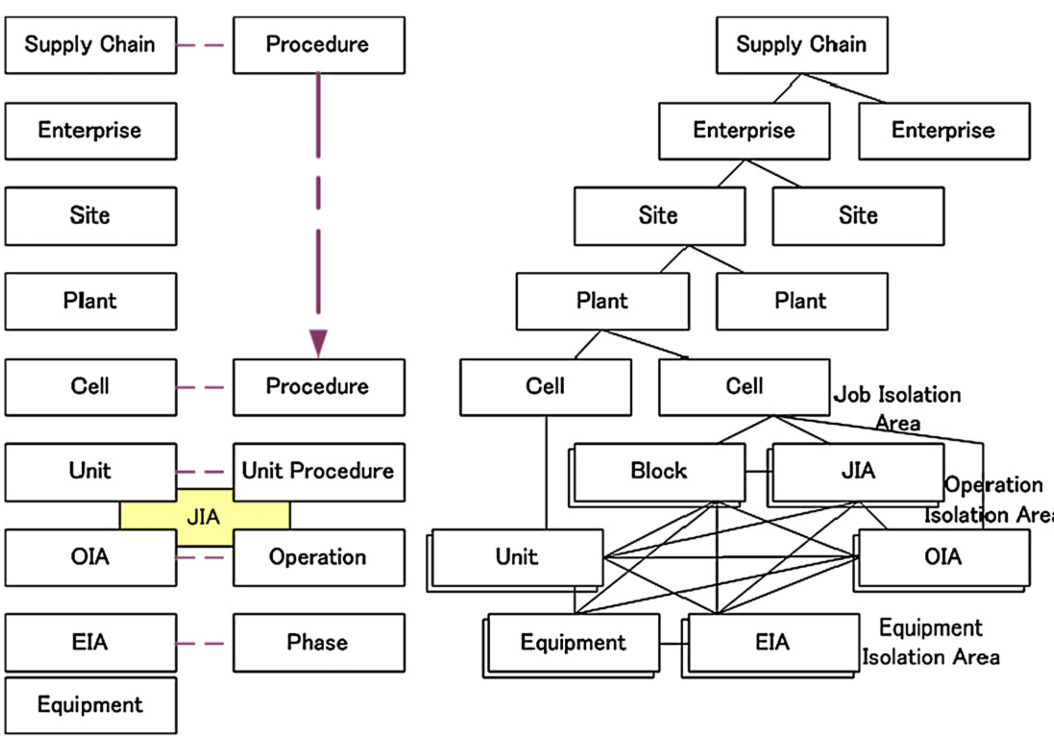

Fig. 4. Topology partitioning views.

3.3. Topology nodes/lines

Topology lines are the topological connection between source and destination, which is required for certain task (i.e. operation, maintenance, safety, etc.). The proposed topology analyzer shows a unique identity for each topology line, which is connected in both sides with topology structure unit. Topology node is the topology connection between source and destination structure units, which might include more than one topology line and structure unit. For example, one line is for coal movement from the input tank to the boiler. Similarly, for the movement of the steam from the boiler to the turbine.

3.4. EIA: equipment isolation area

Equipment is isolated by closing all input and output flow control devices surrounding the equipment. Flow control can be valves, pump, etc. For example, boiler is surrounded with control valves to isolate it from turbine, source input tanks, and NO_x removal unit.

3.5. OIA: operation isolation area

As part of the defined operating procedures, material in coal tank is moved to the boiler. This requires isolating the surrounding topology paths other than the topology path selected to transfer coal (or LNG/LPG). Topology lines are identified and opened where valves are opened and pumps are operated. In such case, operation isolation area (OIA) lines are identified as the surrounding lines for the topological area coal tank/boiler. As part of power plant control, OIA lines are closed to isolate such operation.

3.6. Cell

In the selected case study, the cell is identified as the whole topology area surrounded by all input and output points in the specified P&ID. Input points such as coal tank, LNG/LPG tank, etc., and output points such as chimney tower, grid, etc.

3.7. Block

Block is the logical topology area that represents functional area, as specified during the preliminary design stage. Power plants might have recycle, electricity generation, electricity transmission, and input material blocks, as shown in Fig. 5. For example, the power generation block includes: boiler, pumps, turbine, and condenser. Input material block is connected to power generation block, which is connected to power transmission block and recycle block.

3.8. Unit

Unit is the topology area required to perform unit procedure. In the selected case study, one unit is identified as the topology area covers feeding input materials and generating power, or recycling.

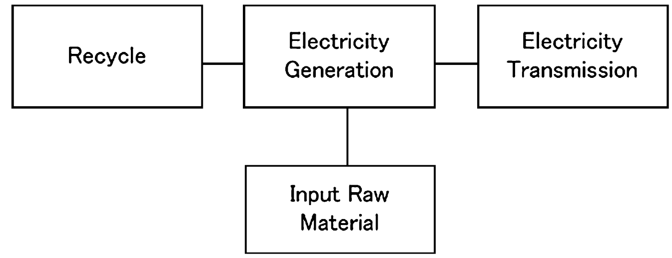

Fig. 5. Power plant block diagram.

3.9. JIA: job isolation area

One job is to generate certain amount of power using input materials and with recycling. Power plant is considered as continuous plant where materials are measured fed into power generation process for continuous power generation. The JIA or job isolation area includes the whole power plant, i.e. similar to cell isolation area. The proposed topology analysis concept of JIA enables the use of job as a dynamic entity of operating procedure and evaluates the corresponding environmental impacts procedure. Job can be defined in terms of procedure, unit procedure, operation and phase. Tasks can be defined for each of these operation levels. For example, one job is defined as feeding input materials, and heating, before power transmission to the output grid. Such job when executed, topology area is isolated to secure the execution of such job. Such topology area is called JIA or job isolation area. For example, if there are more than one output power transmission grid connections, then one job might consider only one output power transmission grid connection, while cell definition includes all grid connections.

Based on these topology partitioning views, operation scenarios and procedures are evaluated in view of environmental impacts and LCA. The proposed topology analyzer will automatically identify each partition including operation lines and isolation lines.

The proposed topology analyzer is based on the described control mechanism where plant topology is modeled on the basis of POOM, as explained in Section 4.

4. LCA-based topology model for thermal power plant

4.1. LCA

LCA is a complex process, which is commonly used to evaluate emission of harmful gases to environment for products or production processes throughout their life cycle. Thermal power plants are very vital energy production process for both social and industrial use, where there are different gases emitted to environment. In this research, different material flows and the emission to environment is studied for thermal power generation plants using LCA. For better understanding and analysis function modeling is proposed using activity models. The flows of necessary material, work activity, and information were defined in each stage and task. The proposed activity models are used to define required information models and database structures that are used to support LCA process. Case study of actual power generation site is used to illustrate the proposed LCA process and associated information models [21].

4.2. LCA measures

The proposed LCA process is applied on the selected power plant. Using the identified set of measures, shown in Table 1, power plant topology and operation can be assessed accurately [21].

In Table 1, environmental measures are elaborated further using detailed measures. For example, the measures for the surrounding environment are further explained using scenery measures, greening and natural resources measures.

4.3. LCA-based power plant topology assessment

Fig. 6 shows certain locations where environmental measures are identified and mapped to power plant topology. Table 2 shows the model elements which are directly linked with environmental measures.

For example, from Table 2, operations related to ventilation should evaluate the corresponding environmental measures to ensure minimum environmental impacts. In order to design environmentally conscious plant operation we proposed topology analysis mechanism which evaluates the different environmental measures at each design step.

5. Topology analyzer

Based on the proposed topology analysis for environmentally conscious power plant operation, topology analyzer and navigator are proposed. Topology analyzer will enable process engineer to view life cycle information as associated with each topology partition. In addition, it will enable operation designer

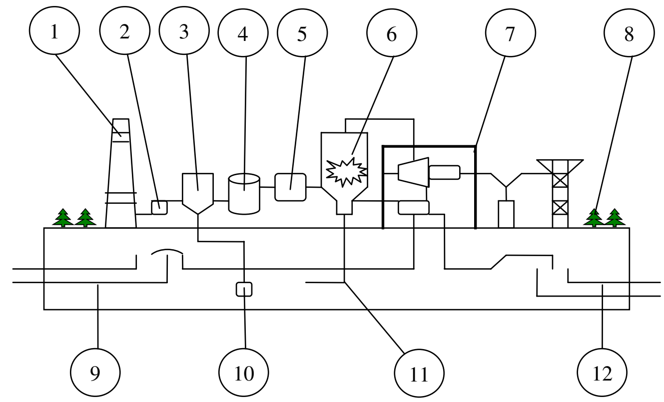

Fig. 6. LCA measures mapped to power plant topology.

to define required topology area for each operation and evaluate each operation scenario in view of the selected topology area. For example, two operation scenarios can be evaluated: (a) 30% coal and 70% LNG use as a fuel for the boiler; and (b) 100% coal. The proposed LCA-based approach evaluated environmental impacts of each operation scenario where appropriate topology area is allocated for each operation scenario. In order to understand the relationships between fuel source and environmental impacts, POOM-based LCA semantic network is proposed as in Section 5.1.

Table 1
Outline of LCA measures for thermal power plants

Items for environmental measures	Details
Air pollution prevention measures	SO_x measures
	NO_x measures
	Carbon measures
	Soot/dust prevention measures
Water pollution prevention measures	Internal drain measures
	Thermal effluent measures
	Leakage prevention measures
Noise, Stink, and vibration measures	Anti-noise measures
	Vibration isolation measures
	Stink prevention measures
Measures for the surrounding environment	Scenery measures
	Greening, natural resources measures
Management of chemical substance	Chemical release investigation
	PCB storage amount
	PCB harmless processing

Table 2
POOM-based LCA measures mapping to plant topology

(1) Set high chimney tower: smoke goes very high with reduced impacts, i.e. thin exhaust	Structure unit/ geometry
(2) Exhaust gas monitoring device: the continuous measurement of density of SO_x and NO_x is performed	Control/operation/ monitoring device
(3) Desulfurizer of SO_x: SO_x are absorbed lime stones are removed after melting with water	Desired behavior/ control device
(4) Electric filtration-type collection dust device: the soot dust is removed	Control/operation/ filtering device
(5) The exhaust gas NO_x is removed: NO_x is removed with the catalyst and ammonia	Desired behavior/ control device
(6) The boiler: the generation of NO_x is reduced by the low NO_x burner, two phase combustion system, and the exhaust gas mixture method	Structure type/ behavior/control
(7) The transformer and the ventilator: prevention measures of noise and vibration are provided	Control/structure type
(8) The greening measures: a suitable tree for the climate in the region around the power plant site is planted where surrounding area around the power plant is made in green	Environment/ external structure
(9) The underwater discharge method: water is discharged, and the range of diffusion of the thermal effluent is reduced	Behavior/control/ operation
(10) The drain measures: dirt and cleaning oil is drained out	Behavior/control/ operation
(11) The fuel measures: low sulfur fuel is used; and	Material/behavior
(12) The deep water supply method: water is obtained from the deepest parts where it is cold water, as for the seawater with a low temperature	Behavior/operation

5.1. POOM-based LCA semantic network

In this study, an integrated framework is proposed to link power plants with environmental impacts. Semantic network is proposed to represent the relationship between POOM-based power plant model elements and the environmental impacts. It shows design or operation feature which is linked with plant structure, behavior, or operation. Model elements are mapped to environmental measures, as explained in Table 2. Environmental measures are linked with greenhouse gases such as CO_2, NO_x, etc., which are mapped to human risks, environmental risks, or social risks. Using the proposed semantic network, it is easy to identify any possible relationships between power plant topology, behavior, and operation model elements and the corresponding environmental impacts, as shown in Fig. 7. In Fig. 7a, POOM-based model elements are mapped to input resources of power plants and conversion technologies, which are mapped to environmental impacts such as social risks, global warming, human health, etc. There are several conversion technologies that are used in power plants, such as Di-Methyl-Ether (DME), and Fischer–Tropsch synthesis light oil (FT). Each conversion technology is mapped to POOM-based process model as well as inventories of greenhouse gases and influence area, such as NO_x/SO_x and global warming, respectively, as shown in Fig. 7b. Social impacts include infrastructure development, social improvements, socio-economic growth expected due to the establishment of certain industry (universities, schools, shopping, medical centers and hospitals, etc.).

The proposed topology analyzer will evaluate total impacts on human health, social welfare, productivity, and biodiversity for each operation scenario and select the scenario with least impacts. In addition to environmental impacts, cost can also be calculated for each operation using a specific topology area, given a certain technology. For example, 1 kg CO_2 emitted to environment will cost human health around 1.19 JPY and will cost social systems 0.54 JPY [22].

5.2. POOM-based hierarchical decision models

The proposed POOM-based LCA assessment will facilitate the evaluation of the different factors that affect each operation scenario, which will support the decision making for process design and operation. This requires an effective decision model based on the different hierarchical levels of both the topology and operation.

There are different decision models that can support such hierarchical models. One useful approach is stochastic-based decision models such as Bayesian and Markov models which are widely used in dynamic systems to support decision making. Also decision trees and other machine learning mechanisms can be used for decision making via learning capabilities [23]. Hierarchical decision trees and similar machine learning techniques are widely used in qualitative reasoning and classification. For example, the hierarchical decision trees can be useful to support the decision making for the LCA assessment for the different hierarchical levels of the topology-operation levels. Another useful technique is AHP or analytic hierarchy process, which is a decision-making model where attributes are evaluated according to preference [24,25]. AHP can be used when there are a limited number of choices, but where each has a number of different attributes, some or all of which may be difficult to formalize. AHP can be used to identify and assign a weight for the selection criteria, and analyze the data collected for the criteria, and hence expedite the decision-making process [24,25]. The proposed structure–operation hierarchy is a design model based on best practices of ISA S88. Such structure–operation hierarchy was further modified

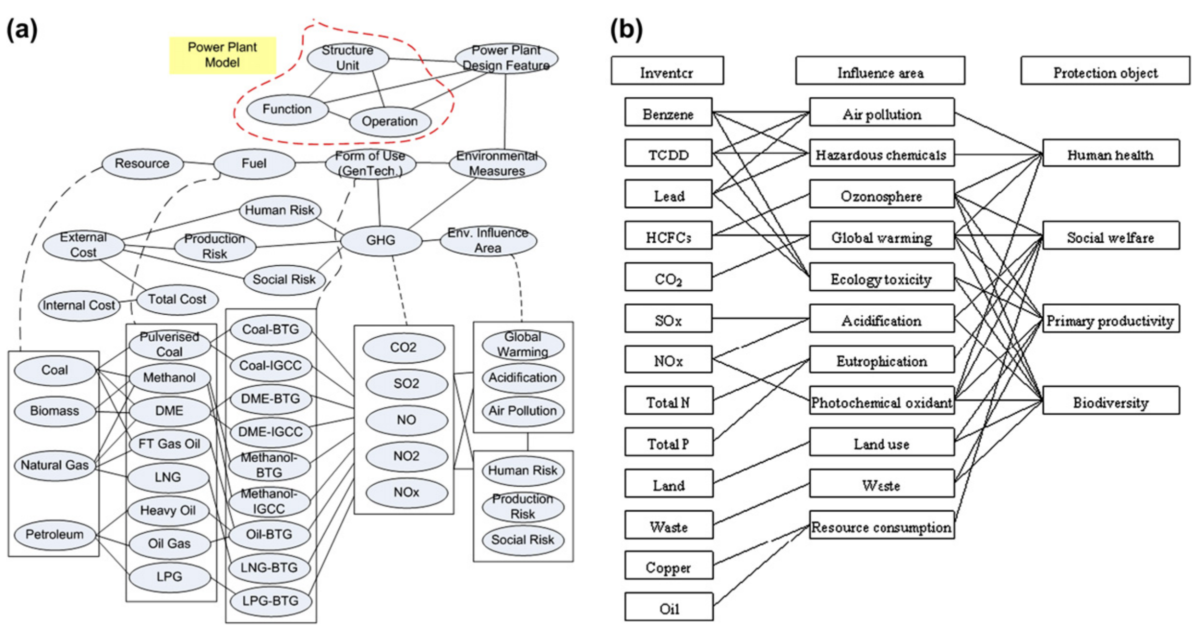

Fig. 7. POOM-based LCA semantic network: (a) mapping power plant process model to environmental impacts; (b) mapping inventory to influence areas and protection objects.

by the author to overcome critical limitations in the direct mapping between structure and operation hierarchical levels. In the modified version of the structure,operation mappings, the use of AHP might support the decision making in the different layers, such as to decide and evaluate different operation and topology partitioning scenarios in the underlying power plant. However, AHP has some criticisms where it is just based on the preferences and human experiences, and might lead to inaccurate or misleading decisions. The proposed decision model based on POOM is systematic, flexible, and can consider different parameters at different model elements and levels as per needs. The proposed decision model is integrated with case-based reasoning, or CBR, and neurofuzzy to synthesize if–then rules [26]. If–then rules are used to continuously tune the developed semantic network for better decisions. In general, the different decisions at each level are evaluated as per static and dynamic values of the different performance indicators, which are accumulated from real time data or simulation. In addition human experience is considered where it is added to the core knowledgebase to fine tune the decisions made. The detailed discussions about decision models are kept outside the scope of this paper due to paper size and readability considerations.

5.3. Integrated topology analysis algorithm (TAA)

The proposed topology analysis algorithm is based on the proposed POOM-based topology model (shown in Section 3 above). The proposed integrated topology analyzer is a useful tool to define the most effective topology partitions suitable for a given operation. This is achieved by defining the different structural hierarchies for each operation as per the proposed operation–structure hierarchy. The selected topology partitioning options are evaluated in view of life cycle activities using the proposed semantic network of life cycle assessment [21] where environmental loads and costs are mapped to power plant process model elements, including structural elements. The best topology partition at each hierarchical level is selected to perform the underlying operation (e.g. job, procedure, unit procedure, operation, OIA, BIA, EIA, or phase). The proposed LCA semantic network (shown in Fig. 7b) is used to map environmental loads such as CO_2 emission and associated costs to protection objects such as human health.

The proposed topology analyzer is used to support operation design and execution, process safety and control, supply chain design and operation, and production scheduling and management. In all cases, topology analysis algorithm, or the TAA, has the following three main steps (as shown in Fig. 8):

1. Defining operation: define operation: job, procedure, unit procedure, operation, and phase.
2. Defining topology partition: define cell, unit, OIA, and EIA.
3. Evaluating LCA/LCC and risks: evaluate risks on health, safety, environment, and the associated costs.

5.4. CAPE-ModE

In view of the proposed topology analysis algorithm, each operation scenario of the underlying power plant is evaluated for each life cycle activity on the basis of LCA and LCC. Each operation scenario is visualized using the developed computer-aided process modeling environment CAPE-ModE [5,7]. Managers and engineers will be able to visualize environmental impacts and life cycle assessment values for any topology area, partition, or structure unit. In the background (i.e. left side) of Fig. 9, the flowsheet of the underlying power plant is shown

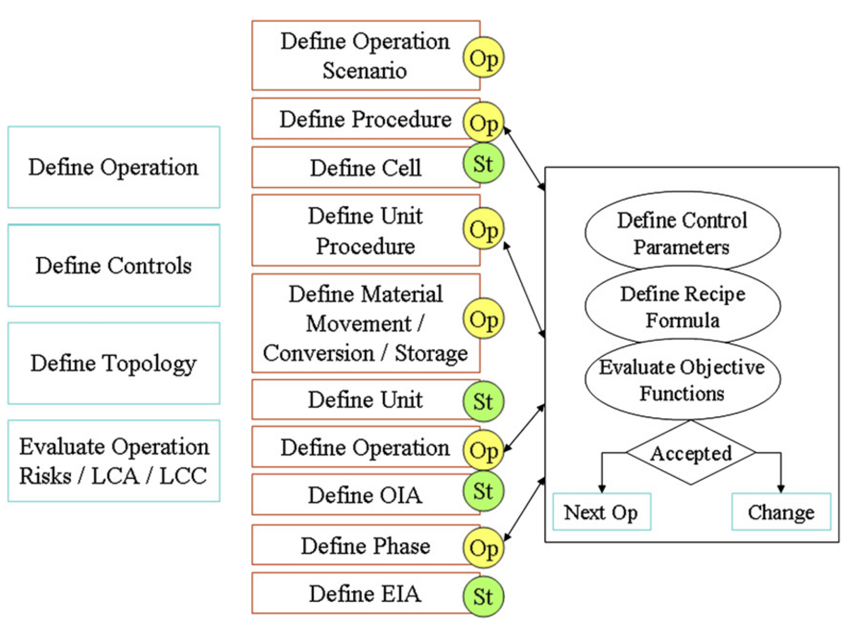

Fig. 8. Topology analysis algorithm (TAA).

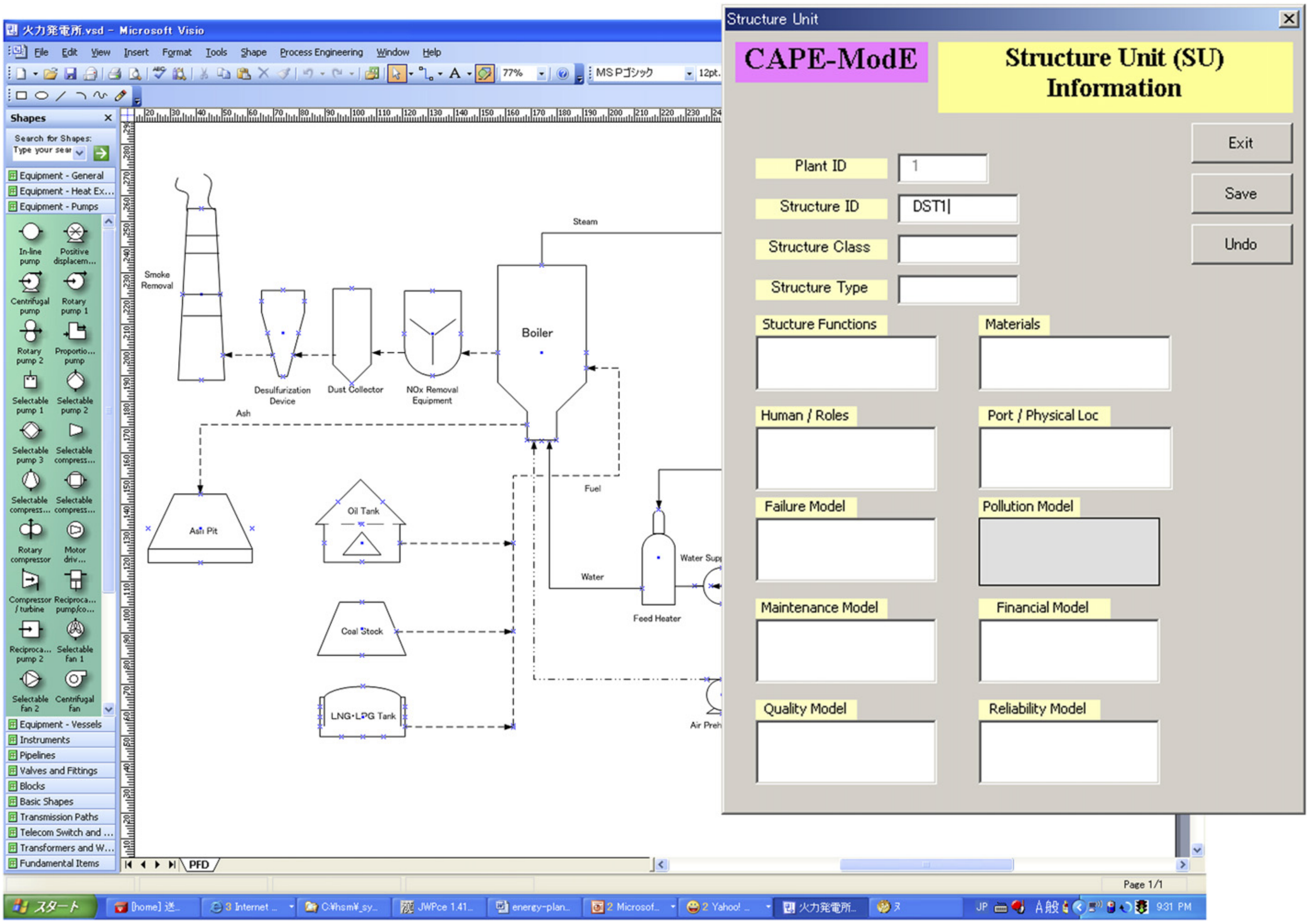

Fig. 9. Topology analysis and process knowledge as shown in CAPE-ModE.

within CAPE-ModE. For a certain operation, engineer can visualize total pollution, for example, associated with such operation in the selected topology partition (i.e. boiler with source-x and conversion technology-y). The window in the right hand side of Fig. 9 will be displayed showing all related information of the topology area, partition, and structure unit, such as pollution level, along with the associated environmental impacts on global warming, human health, social welfare, and productivity. This is essential to enable engineers and managers to understand in real time basis the consequences of each operation for better control and management.

6. Conclusion

Plant operation starts from process design where it is defined incrementally while designing the underlying process. Operating procedures are evaluated using performance indicators from life cycle activities. In order to provide environmentally conscious operating procedures, environmental impacts are evaluated at each stage of operation design. To make this task easy, systematic topology analysis method is proposed in view of ANSI/ISA-S88 standards [6]. Operation isolation area (OIA), job isolation area (JIA), equipment isolation area (EIA), cell, unit, and block topology partition mechanism is identified and used to evaluate environmental impacts at each stage. To facilitate such target, case study of thermal power plant is used where environmental measures are identified in view of POOM modeling methodology and mapped to plant structure, along with the associated behavior and operation. The proposed topology automated partitioning will facilitate the automatic identification of the most effective structure areas that are suitable for the underlying operation, in view of environmental impacts. TAA or topology analysis algorithm is proposed to achieve such target where it has been implemented within CAPE-ModE, which is an effective tool that supports the design of plant operation with the considerations of environmental impacts. This will enable production plants to reduce environmental impacts as per stated regulations and policies for cleaner production systems.

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