Cost-effective, MAS-based, reefer system at container terminals

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Abstract. Nowadays, electric power demand of container terminals is related to particularly flexible loads. Among the most significant flexible loads, are the refrigerated containers, known as reefers. On average, reefers are responsible for 47.87% of the total energy consumption of container terminals. The control of the numerous reefers, is difficult to be achieved with conventional control systems. Multi-agent systems (MAS) have been proved to be very efficient in complex systems and, as it is shown in this paper, they can also be effective for container terminals. In this paper, a distributed demand-response system using MAS, implemented in JADE, is proposed for power demand management for reefers, at container terminals. A fuzzy logic-based system is exploited to estimate the reefers' desired utilization factor and is integrated to the developed MAS. The efficiency of the proposed method is evaluated by detailed simulations with real data of a large container terminal. A reduction of 44,68% to total energy cost of reefers at a container terminal was achieved.

Keywords: multi-agent systems · JADE · reefers · micro grid · fuzzy systems · real data · container terminals · energy consumption.

1 Introduction

Container terminals are nodal points of the international transport network, transferring huge amounts of commodities and playing a key-role in the energy systems [13,35,1]. In order to move towards the direction to sustainable terminals, power management systems need to be more efficient [39,24,20,22,7,49,5,6,4].

An important component of the container terminal micro grid [34,2] are the refrigerated containers, known as reefers that can be considered as thermostatically control loads, which are used for storing and transporting refrigerated goods in a port terminal. As reefers have a potential to serve as a responsive load, they can be used for actively modifying the power consumption. Nowadays, on average, reefers are responsible for 47.87% of the total energy consumption of container terminals [30]. The control of the numerous reefers, is difficult to be achieved with conventional control systems.

The key feature of demand side management is the combined exploitation of load control, operation rescheduling and energy storage. The existence of loads with a degree of flexibility is the key for efficient demand side management. Reefers, are hosted in large numbers in container terminals. Reefers are very flexible loads in time and power consumption and are expected to be a major component of future smart container terminal electric energy systems. Thus, as port energy systems are changing rapidly and become more complex and efficient, Power Management Systems are needed [1]. The load management in such systems using a single centralized controller or traditional optimization techniques requires a great amount of computation resources making the application of centralized optimal control systems quite difficult and challenging [53,26]. Load management mainly focuses on matching load demand with power production while achieving certain objectives, such as reducing operation cost, ensuring power system stability and reliability etc. In order to develop sustainable port terminals, power management systems need to be more efficient.

Multi-Agent Systems (MAS) have been considered for applications in power engineering mainly due to their distributed control, where the overall optimization problem is decomposed into smaller sub-problems that individual controllers can solve cooperatively [53,26,47]. In MAS, each controller manages a single system unit, and groups of controllers report to higher-level coordinators that manage the interaction between the various subsystems. An intelligent agent is assigned to each controller and all agents together compose the MAS. This system has been proved very effective in solving complex optimization problems where the detailed model of the entire controlled system is difficult to be obtained and traditional control techniques are proved insufficient. MAS technology has been widely exploited in power engineering [47,24,23,42,29,21,12].

In [17], the authors used simulated data and a MAS architecture simulated in MATLAB. A fuzzy logic- based system is exploited to estimate the reefers' desired utilization factor and it is integrated to the developed MAS, in order to reduce the operation cost of reefers. Several empirical approaches were investigated under the E-harbors project, such as the ports of Hamburg and Antwerp [52]. Others works using the same real dataset [31,14], employed an optimization algorithm to just reduce the reefers' peak demands. Other research works [51,33,30,40,28] examine energy costs of reefers, either from a different point of view or without providing quantitative results.

For this work we used JADE [9], a standardized, state of the art, platform that has proved its worth in real world applications in the smart grid [41,8,3,43,27,36,16]. Our research, combines a MAS architecture with real data, the only available, and a fuzzy-logic based approach. The key findings of our research, is that a MAS-based, cost-effective, reefer system at container terminals can improve significantly the state of the art. The implementation of the method relies on the exploitation of a hierarchical MAS [37]. The proposed method is designed in such a way that it allows for scalability and adaptability, enabling its application to diverse micro grid configurations and sizes.

In Section 2 we outline the MAS architecture and its elements. Then, in Section 3, we show cases of realistic simulation outcomes, assess their implications and discuss our findings. We conclude in Section 4.

2 Agent Modeling

Reefers stay in the container terminal for approximately two to three days and they consume electric power to preserve their temperature sensitive cargo. Reefers rely on external sources of power, i.e., the electric grid. They have the capability of controlling the temperature from -30, -40$°C$ up to 30, 40$°C$. When, a well-insulated reefer is switched off, its internal temperature increases approximately by 1$°C$ per 9 hours. Nominal power consumption of a typical reefer is approximately 10 -15 kW, while its average utilization factor ranges between 0.3 and 0.4 [52]. It becomes apparent that reefers are very flexible loads and can be easily shifted in time.

A Multi-Agent System (MAS) is adopted in the examined problem. The driver to choose MAS was that they are able to achieve optimization objectives in very complex systems that might be difficult to attain with a centralized controller. Moreover, each component of the grid is semi-autonomous in the sense that it can manage its local operation, being dependent for applying centrally defined strategies. Thus, a failure in one component will not result to total collapse of the system. Moreover, mitigations can include the launch of agents that can take over a lost role (especially if that one is in the top of the hierarchy).

We utilized a methodological approach for system analysis and design, following the Agent Systems Engineering Methodology (ASEME) [48], as it has been recently used successfully for engineering MAS for the smart grid [47,15] and is referred to by surveys in the field [18]. ASEME leverages statecharts and the unified modeling language (UML) for system analysis and design models. It remains neutral regarding agent architecture and mental model, empowering designers to choose architecture types and agent attributes, thereby supporting diverse agent architectures.

Additionally, ASEME advocates for a modular agent design approach and utilizes the intra-agent and inter-agent control concepts. Intra-agent control coordinates different modules implementing an agent's capabilities to determine its behavior, while inter-agent control defines protocols governing the coordination of agent societies. ASEME allows the seamless integration of the inter-agent control model in the intra-agent control model as they follow the same formalism—i.e., statecharts [19,46]. Finally, it supports code generation for JADE [45].

Capabilities are further broken down into individual activities. For example, consider a reefer manager's capability to respond to a request to lower consumption in the following time-lapse. This capability can be decomposed into specific tasks, such as to wait at the appropriate channel for receiving the request, select the appropriate reefer agents to halt consumption and reply promptly. Once

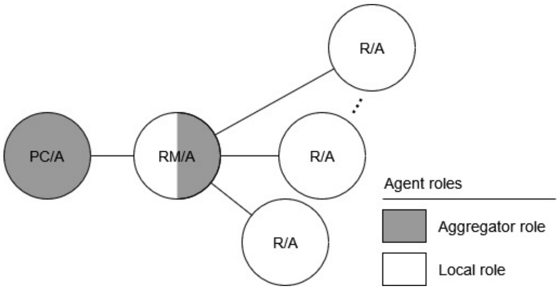

Fig. 1. MAS Architecture

these activities are identified, the next step is to link them to specific functionalities, such as methods, algorithms, technologies, or techniques. This linking process is a crucial managerial task, as each activity can be associated with different functionalities. For instance, the decision-making activity of selecting the reefers can be linked to a fuzzy rules based sub-system, to an argumentation-based approach, or to a utility function, suggesting a multi-criteria decision analysis method.

In recent years, both commercial and open source agent development tools have become available. For developing our MAS we selected JADE. JADE is a JAVA framework for developing FIPA compliant MASs, not imposing any specific agent internal architecture. According to the adopted concept the agent roles can be categorized into two major types:

- *Local role* that is responsible to represent a single component of the port power system,
- *Aggregator role* that is responsible to aggregate the responses of the local roles and also send to them command signals

Using these two roles we can identify three agent types in our architecture:

- *Reefer agent (R/A)*, which realises the local role and corresponds to a reefer in the microgrid. The R/A is responsible for the modeling of the operation of the reefer it controls
- *Reefer Manager agent (RM/A)*, which realises the aggregator role for the R/A and the local role for the Port Controller agent
- *Port Controller agent (PC/A)*, which realises the aggregator role for the RM/A

In Figure 1 the MAS architecture is presented. It highlights the agent-based architecture for modeling the port power grid and shows its advantages. On the top of the figure we have the PC/A. The PC/A communicates with RM/As, which, in turn, communicate with the R/As. The nature of the communication is to share relevant information bottom-up and to give directions (top to bottom).

The R/As estimate the flexibility of reefers to change their power demand. They can send this information to the RM/A and accept directives to change their state. The RM/A aggregates the flexibility information from all the R/A and can share it with the PC/A. It also accepts directives for power consumption changes from the PC/A. Finally, the PC/A, at each time interval requests the RM/A aggregated flexibility and estimates the total power demand of reefers that reduces their operation cost. Moreover, PC/A calculates a marginal value of flexibility and forwards it to RM/A. It sends these decisions in the form of a directive to the RM/A. Marginal flexibility ensures that if reefers with a higher flexibility change their operation state then accurate tracking of the set-point of the power demand of reefers is ensured.

2.1 Reefer Agent (R/A)

The model described next estimates the flexibility of each reefer to change its operation state and the power demand. The following functions, as modelled and in the order presented next, are performed by R/A. To calculate its flexibility, the R/A estimates, with the model described next, the the change of the internal temperature of the reefer over the next time interval Δt. The internal temperature of the i^{th} reefer at time $t+\Delta t$ is estimated according to ([23,24,50]):

$$T(i,t+\Delta t) = T(i,t) + \Delta T_{amb} \cdot (1 - e^{-\frac{A\cdot k}{m(i)\cdot c_p(i)}\Delta t}), StR(i,t) = 0 \tag{1}$$

$$T(i,t+\Delta t) = T(i,t) - \frac{P_{\text{reefer,cool}} \cdot \Delta T}{m(i) \cdot c_p(i)}, StR(i,t) = 1 \tag{2}$$

where, A is the surface Area of Reefer (m^2), k is the thermal Insulation of Reefer ($W/m^2 \cdot^\circ C$), m is the mass of Cargo (kg), c_{p} is the specific heat of cargo ($kJ/kg \cdot^\circ C$), $StR(i,t)$ is the operation State of the Reefer i, at time t, $StR(i,t) = 1(0)$ if the reefers is switched on(off), ΔT_{amb} is the temperature Difference ($^\circ C$)= Ambient Temperature - Return Air Temperature ($^\circ C$), $P_{\text{reefers,cool}}$ is the refrigerating power provided to reefer's content, (in kW) , t is the time (Seconds), Δt is the duration of the time intervals and $\Delta T(t)$ is the temperature effect of reefer in Time ($^\circ C$) .

The estimated internal temperature of the i^{th} reefer is used together with its upper and lower limits to obtain the flexibility of each reefer to change its operation state as in the equations below. Assuming that the content of the i^{th} reefer is maintained above the minimum temperature T_{min} and below the maximum temperature T_{max} the flexibility of the i^{th} reefer to change its operation state is defined as ([23,17]):

$$FL^{\downarrow}_{reefer}(i,t) = \frac{T_{max}(i) - T(i,t+\Delta t)}{T_{max} - T_{min}} \tag{3}$$

$$FL^{\uparrow}_{reefer}(i,t) = \frac{T(i,t+\Delta t) - T_{min}(i)}{T_{max} - T_{min}} \tag{4}$$

$$FL(i,t) = 0, if t_{on(off)} < t_{on,min(off,min)} \tag{5}$$

where, $FL^{\uparrow}_{reefer}(i,t)$ is the flexibility of the i^{th} reefer to increase its power demand,at time t, $FL^{\downarrow}_{reefer}(i,t)$is the flexibility of the i^{th} reefer to decrease its power demand, at time t, $T_{max(min)}$ is the maximum (minimum) temperature of reefer's content (in $°C$), $t_{on(off)}$is the last time a reefer was switched-on(off) and $t_{on,min(off,min)}$ is the minimum time the reefer should be continuously switched-off(on) .

R/A provides as output the flexibility of the reefer to change its state of operation and the resulting power demand change. The possible change of the electric power demand of the i^{th} reefer is obtained as in the following:

$$\Delta P_{reefer}(i,t+\Delta t) = \begin{cases} P_{reefer}(i,t), & ifStR(i,t) = 0 \\ -P_{reefer}(i,t), & ifStR(i,t) = 1 \end{cases} \tag{6}$$

where, $P_{\text{reefer}}(i,t)$ is the electric power consumed by the i^{th} reefer (in kW) at time t, and $\Delta P_{reefer}(i,t+\Delta t)$ is the power demand change offered by a reefer for the next time interval.

2.2 Reefer Manager Agent (RM/A).

The RM/A is placed one level above the R/A in the proposed MAS hierarchical structure (2^{nd} level). It aggregates the flexibility change of power demand curves it receives from all the reefers it supervises. The PC/A calculates how much the power demand of the port should change in order to achieve its next interval goal, also referred to as *set-point* and sends the directive to the RM/A. Also, by sorting in descending order the flexibilities of the reefers, the PC/A computes the *marginal flexibility*, to achieve the necessary change to the power demand of the PC/A. Subsequently, the RM/A sends directive to the reefers with flexibility above the marginal one to change their state.

Estimation of power demand set-point of all the reefers. A fuzzy-logic-based system [54,25,38]s used to calculate the desired *utilization* factor of all the reefers with respect to the level of the electricity *price* and their aggregated *flexibility* to increase power demand. Each of the fuzzy sets used for the electricity price, utilization factor and flexibility of all the reefers, corresponds to the linguistic variables: *small*, *medium*, *big* and *large*. The membership functions used for the fuzzification stage are depicted in Figure 2. The rules used for the estimation of the utilization factor of the reefers are given below. A defuzzification strategy based on centroids is used to generate a crisp value for the desired utilization factor [17]:

RULE 1: IF price IS large THEN utilization IS large;
RULE 2: IF (flexibility IS small) AND (price IS large) THEN utilization IS large;
RULE 3: IF (flexibility IS big) AND (price IS large) THEN utilization IS small;
RULE 4: IF (flexibility IS large) AND (price IS big) THEN utilization IS small;
RULE 5: IF (flexibility IS medium) AND (price IS small) THEN utilization IS large;
RULE 6: IF flexibility IS small THEN utilization IS big;
RULE 7: IF flexibility IS large THEN utilization IS small;
RULE 8: IF price IS big THEN utilization IS large;
RULE 9: IF (flexibility IS big) AND (price IS medium) THEN utilization IS large;

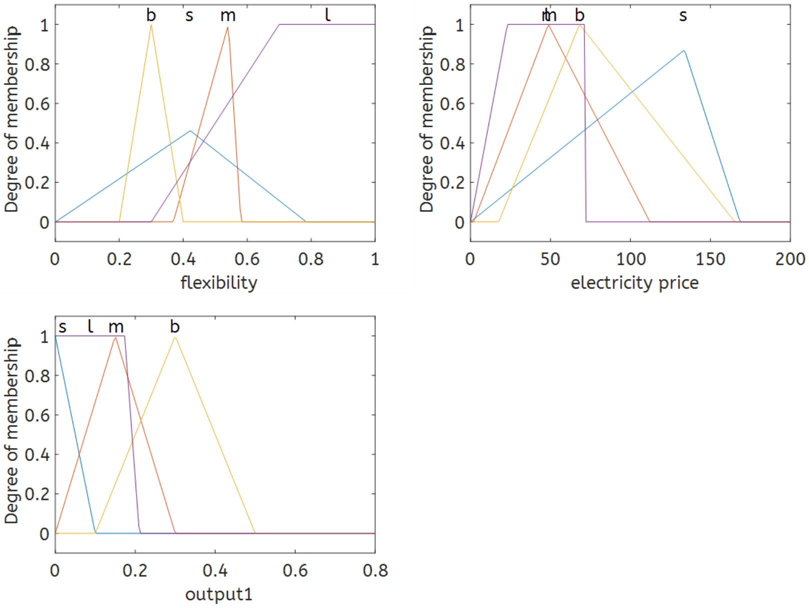

Fig. 2. a) Membership function of flexibility of the reefers to increase its power demand; b) Membership function of the electricity price; and c) Membership function of the utilization factor (output1) of all the reefers. The linguistic variables are small (s), medium (m), big (b) and large (l)

RULE 10: IF (flexibility IS big) AND (price IS small) THEN utilization IS medium;
RULE 11: IF (flexibility IS small) AND (price IS small) THEN utilization IS large;
RULE 12: IF (flexibility IS small) AND (price IS medium) THEN utilization IS large;
RULE 13: IF flexibility IS medium THEN utilization IS medium;

The aggregated utilization factor, *UF*, of all the $N_{reefers}$ reefers, and the respective flexibility to increase its power demand, $FL^{\uparrow}$, are given below [17]:

$$UF_{reefers}(t) = \frac{\sum_{i=1}^{N_{reefers}} P_{reefer,nom} \cdot StR(i,t)}{\sum_{i=1}^{N_{reefers}} P_{reefer,nom}} \tag{7}$$

where, $UF_{reefers}$ is the utilization factor (set-point) of all the reefers (in [0 1]) and $P_{reefer,nom}$ is the nominal electrical power consumption of a reefer (in kW).

$$FL^{\uparrow}_{reefers}(t) = \frac{\sum_{i=1}^{N_{reefers}} \cdot (1 - StR(i,t)) \cdot P_{reefer,nom}(i) \cdot FL^{\uparrow}_{reefer}(i,t)}{\sum_{i=1}^{N_{reefers}} P_{reefer,nom}(i)} \tag{8}$$

where, $FL^{\uparrow}_{reefers}$(t) is the flexibility of all the reefers to increase theirs power demand, at time t and $FL^{\uparrow}_{reefer}(i,t)$ is the flexibility of the i^{th} reefer to increase its power demand, at time t. The set-point of the electric power consumption of the Manager of the reefers is calculated below:

$$P^*_{reefers}(t) = UF^*_{reefers}(t) \cdot \sum_{i=1}^{N_{reefers}} P_{reefer,nom}(i,t) \tag{9}$$

where, $UF^*_{reefers}(t)$ is the desired utilization factor (set-point) of all the reefers (in [0 1]),at time t, and $P^*_{reefers}(t)$ is the desired electrical power consumed by all reefers in port (in MW) in the 2^{nd} level, at time t .

2.3 Port Controller Agent (PC/A).

The PC/A is the agent placed on the top of the hierarchy (3^{rd} level). PC/A receives the aggregated responses from all R/A via aggregation by the RM/A. In this experiment PC/A, controls only one Manager Agent, the RM/A, and acts like a dummy agent. But in our ongoing research, to simulate all the flexible electrical loads of a port terminal, we have plenty manager agents and its role is very crucial. For this reason we take the decision to use, in this case study, the "dummy" PC/A. The PC/A receives the aggregated responses from RM/A and is responsible to compute the suitable ΔP power which will fulfill the PC/A operation goals. The PC/A calculates how much the power demand of the port should change in order to achieve its set-point, which is either the moving average across the window of observation, or a given value. This is then sent to RM/A as a directive. To compute ΔP the following equations apply. The desired electric power consumed by all reefers in the port terminal (in MW), in the 3^{rd} level ,$P^*_{port,reefers}$, is calculated as:

$$P^*_{port,reefers}(t+\Delta t) = P^*_{reefers}(t+\Delta t) \tag{10}$$

where, $P^*_{reefers}$is the desired electrical power consumed by all reefers in the port (in MW) in the 2^{nd} level.

Then, $P^*_{port,reefers}$,is adjusted over the next time interval by estimating the respective set point $\bar{P}_{\text{port,reefers}}$ as in the following equation:

$$\bar{P}_{port,reefers}(t+\Delta t) = P^*_{reefers}(t+\Delta t) \tag{11}$$

where, $\bar{P}_{port,reefers}$ is the set-point of the electric power consumption of all the reefers (in MW) in the 3^{rd} level.

The respective power demand set-point of the electric power consumption of all the reefers (in MW) in the 2^{nd} level $\bar{P}_{reefers}(t+\Delta t)$ is then calculated according to:

$$\bar{P}_{reefers}(t+\Delta t) = \bar{P}_{port,reefers}(t+\Delta t) \tag{12}$$

Finally, the required change of the current power demand of all the reefers, $\Delta P_{\text{reefers}}$(t), is estimated:

$$\Delta P_{\text{reefers}}(t+\Delta t) = \bar{P}_{reefers}(t+\Delta t) - P_{\text{reefers}}(t) \tag{13}$$

In order to apply the required change of the power demand of all the reefers estimated above, the PC/A does the following:

- Collects the offers for power demand change received by the RM/A and sorts them in descending flexibility.
- The point where the sum of the power demand change above becomes greater than or equal to ΔP is the marginal flexibility.
- The marginal flexibility is sent to the RM/A.

3 Case Study

3.1 Simulation Data

When doing simulations the use of real data is significant [32,30]. This case study is based on real data [50], collected at a container terminal. This data set provides all reefer data, such as its dwell-time at terminal, its mass, set point, etc. This dataset is the only available in the public domain. Port terminal authorities, although they have similar data for their terminals, are loath to provide them to researchers. The lack of real-world data and its significance for validating results has been mentioned in the literature [30]. The period of measuring for our dataset was from the 1^{st} of January 2014 to the end of January 2015. The reefer cooling capacity is assumed to be equal to the electric power consumption and the cooling power. We have also assumed that all reefers immediately after plugging-in are set to cooling mode.

3.2 Simulation Scenarios

The simulation results that we present, are based on data from the first two days of July, with a step interval equal to 1 minute (simulation Tick=1 minute). Thus, the total simulation time is 2880 ticks. We get similar results if we use other periods in the dataset. In this simulation interval, 879 Reefers dwelled at the port terminal. We run four scenarios:

- *dummy scenario, without MAS Control*, i.e. there are no directives and the flexibility of the reefers fluctuates continuously between 0 and 1 with different slopes when cooling and no cooling.
- *MAS control*, i.e we have directives from the PC/A to the RM/A and from the RM/A to the R/A's, and flexibility changes as ordered to achieve its set-point, which is computed as the moving average across the window of observation.
- *MAS with set-point*, where the port terminal tries to achieve a desired, predefined power consumption of all the reefers (set-point)
- *MAS with cost consideration*, where the port terminal tries to achieve a minimum power cost, taking into account the fluctuations of the electricity price over time.

3.3 MAS Modeling

This section on one hand aims to help the reader understand the functionality of the MAS and on the other hand to get an insight in the flexibility of our architecture that allows the port roles to connect dynamically. This model applies for the last three of the above scenarios, i.e. those with MAS. When engineering the agents using ASEME, we first define the agent interaction protocols (inter-agent control model) as they are re-used as capabilities when defining the agents.

We provide as an example, the *GetReeferFlexibilityAndConsumption* protocol between a local role (R/A) and an aggregator role (RM/A). It is defined as a statechart (following the semantics of [19] and the graphical model syntax of the ASEME statechart editor [48]) with the AND-state *GetReeferFlexibilityAndConsumption* as the root (see Figure 3). The root state engulfs the whole statechart. AND-states (depicted with a light blue color label) contain OR-states, and being in an AND-state entails being in all its OR-states simultaneously, implying that the latter are executed in parallel (also called orthogonal components). OR-states (with yellow-colored labels) contain other sub-states, only one of which can be active at any time.

START-states (denoted by black dots) indicate the initiation of execution, while END-states (depicted as black dots enclosed within a circle) mark the conclusion of execution. START- and END-states are pseudo states, i.e. are used to indicate where execution starts and ends, but the statechart cannot stay in these. BASIC-states (shown in green) are where agent activities are executed.

In Figure 3 we have two OR-states, one showing the behavior of the local role (R/A) within the protocol, *GetReeferFlexibilityAndConsumption_ Reefer* and one for the aggregator role (RM/A), *GetReeferFlexibilityAndConsumption_*

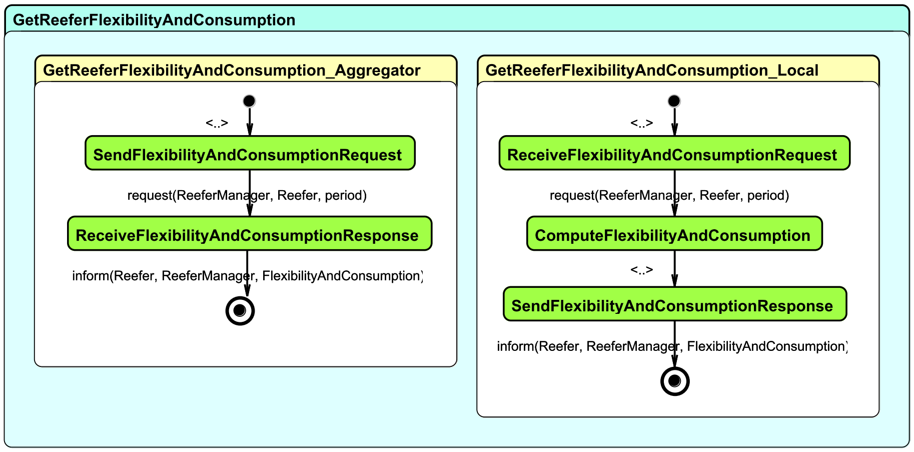

Fig. 3. The *GetReeferFlexibilityAndConsumption* protocol by which the reefer manager role gets information about the reefers consumption and flexibility for the next reporting period.

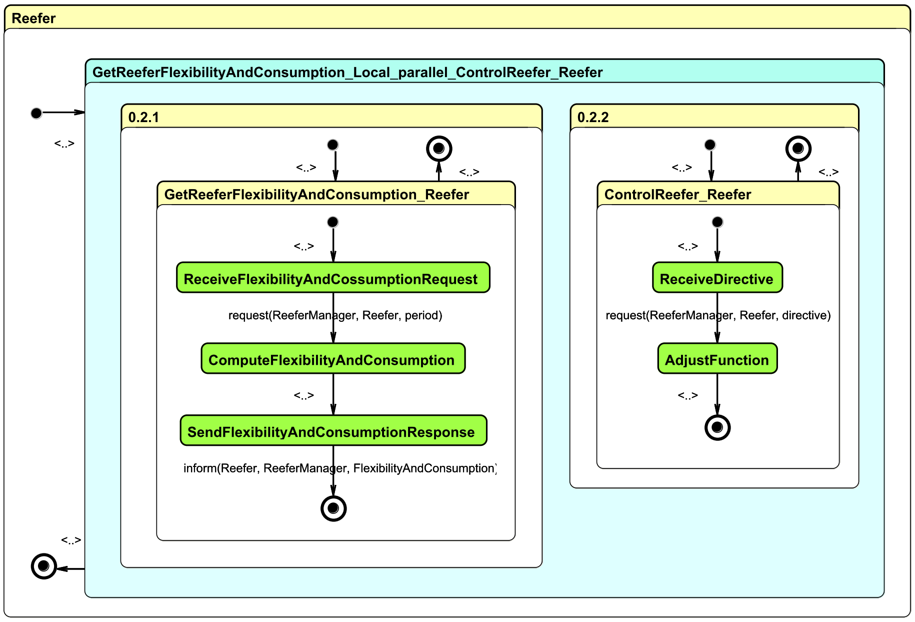

Fig. 4. Reefer Agent Statechart

ReeferManager. Both are executed in parallel. The exchange of messages synchronizes their execution.

Each transition from one state (source) to another (target) is labeled by an expression, whose general syntax is $e[c]/a$, where e is the event that triggers the transition; c is a condition that must be true in order for the transition to be taken when e occurs; and a is an action that takes place when the transition is taken. All elements of the transition expression are optional [19].

Transitions are usually triggered by events. Such events can be a sent or received inter-agent message, a timeout, and, the completion of the executing state activity. Note that each state automatically starts its activity on entrance. A message event is expressed by $P(x, y, c)$ where P is the performative, x is the sender role, y the receiver role and c the message body [44]. States starting with the word *Receive*, indicate waiting states for a message to arrive. States starting with the word *Send*, indicate states that prepare and send a message.

In Figure 3 the local role (executing the *GetReeferFlexibilityAndConsumption_Reefer* orthogonal component) waits to receive a message. As soon as it receives the message event with performative *request*, with the RM/A as sender and with itself as the recipient it exits the *ReceiveFlexibilityAndConsumptionRequest* state and enters the *ComputeFlexibilityAndConsumption* state. After it finishes the computation it exits this state and enters the *SendFlexibilityAndConsumptionResponse* state. In the latter it prepares and sends the message with performative *inform*, with itself as sender and with the Reefer Manager as recipient. This causes it to exit the protocol (it finished). Likewise, the Reefer Manager starts by sending the *request* and then waits for the *inform* message and itself terminates the protocol execution.

To show how the agents intra-agent control model integrates protocols, we provide R/A's model in Figure 4. The OR-state *Reefer* is the root (see Figure 4). The *Reefer* state has a START-state, an AND-state (*GetReeferFlexibilityAndConsumption_ Reefer_ parallel_ ControlReefer_ Reefer*) and an END-state. Thus, as soon as execution starts, the *Reefer* enters the AND-state. Its OR-substates are *0.2.1* and *0.2.2*. These are OR-states and the statechart execution engine enters them and searches for their START-states to show where execution begins.

Thus, the *Reefer* enters the BASIC-states *ReceiveFlexibilityAndConsumptionRequest* (in the first orthogonal component) and *ReceiveDirective* (in the second). These are both activities that wait to receive messages. These messages are related to two different protocols, i.e. the *GetReeferFlexibilityAndConsumption* and the *ControlReefer* protocols. The names of the OR-states in the orthogonal components indicate the name of the protocol (*GetReeferFlexibilityAndConsumption*, *ControlReefer*), followed by an underscore and then the role of the agent in the protocol (*Reefer* in this case).

3.4 Simulation Results and Discussion

Scenario 1. Figure 5(a), displays the flexibility (normalized temperature) of a typical random reefer, that stays in port from Tick=20, till Tick=2790, which fluctuates between 0 and 1 with different slopes when cooling and not cooling, for the dummy scenario. This represents the fact that the temperature fluctuates between minimum and maximum value continuously. Also, Figure 6(a) displays the total port terminal consumption, from Tick=120, till Tick=2880, for the dummy scenario.

Scenario 2. Figure 5(b) displays the flexibility of a typical reefer, from Tick=20, till Tick=2790, in the case of MAS control. The difference with regard to the previous scenario is that flexibilities change before they reach 1, and, respectively the temperature does not fluctuate between minimum and maximum value. Also, Figure 6(b) displays the total Port Terminal Consumption, for the same period, as previously. We observe significant differences, to the total reefers consumption over time, compared to the first – dummy scenario. This is due to the action of the MAS control.

Scenario 3. In this scenario, a desired set point, 900 KW, which is less than the average consumption in the second scenario (see Figure 6(b), was set from Tick=700 till Tick=2000. At Figure 7(a) the results are presented. It is observed that the port terminal total reefers consumption followed the predefined set point very well. This is due to the act of MAS Control.

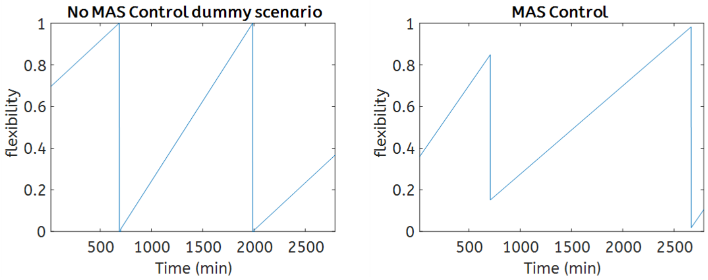

Fig. 5. a) Flexibility variation over time of a typical reefer, without MAS, and b) Flexibility variation over time of a typical reefer, with MAS control

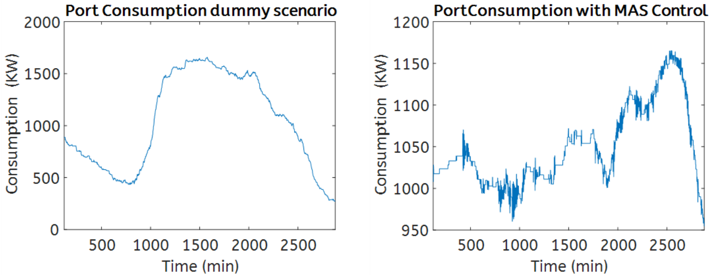

Fig. 6. a)Port Terminal Total Reefers Consumption over time without MAS and b)Port Terminal Total Reefers Consumption over time, with MAS

Scenario 4. Finally, in the fourth scenario, we employed MAS control with cost information included. Cost information is considered with the use of a not constant, but time - varying evolution of the electricity price over time. The cost information was taken into account with the integration the fuzzy-logic subsystem described in paragraph 2.2 into the MAS. The fuzzy-logic sub-system was tuned and trained with Matlab. For the implementation of the fuzzy-logic sub-system in java we used the jFuzzyLogic package [10,11]. In Figure 7(b), the simulation results are shown. As we can see, due to the act of the MAS control, the desired total reefers power consumption computed by the fuzzy sub-system, and the actual consumption, are very close to each other, over time.

It is obvious that the applied control method allows reefers in the port to change their power demand as desired in order to reduce their operation cost. In Figure 8(a), we give the marginal flexibility, where we observe that the marginal flexibility varies considerably, between 0.15 and 1.0. In figure 8(b) we provide the sample evolution of the electricity price over time that we used for this scenario. Similar results were taken with other curves of electricity price. This evolution of the price is used for computing the desired reefers consumption. In Figure 8(c), the produced by the simulation desired utilization factor is shown, which varies between 0.15 to 0.25. In figure 8(d) we provide the estimated required change of the current power demand of all the reefers by the PC/A. The estimated change

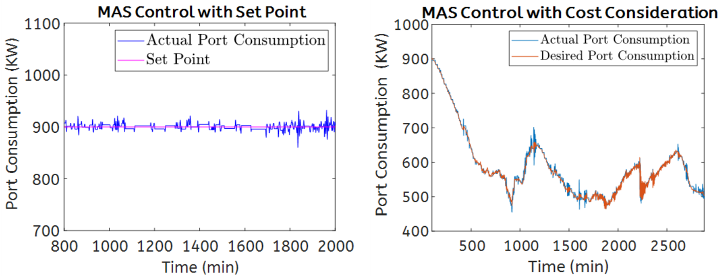

Fig. 7. a) Port Terminal Total Reefers Consumption over time, with MAS control and desired Set Point and b) Port Terminal, Total Reefers Power consumption over time actual and desired

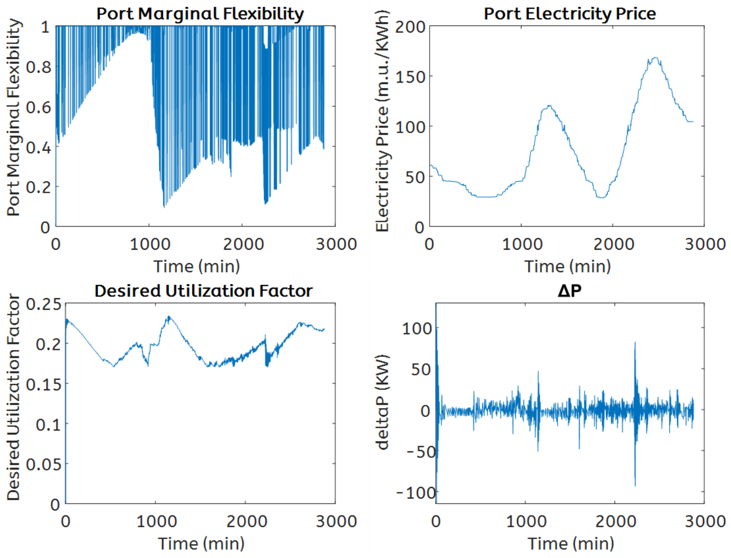

Fig. 8. a) Port Marginal Flexibility b) Electricity Price over time c) Desired Utilization Factor and d) the estimated required change of the current power demand of all the reefers, at the PC/A level

of the current power demand of all the reefers, $\Delta P_{\text{reefers}}(\mathrm{t})$ balances around zero with small values and some spikes.

Discussion and related work. In Table 1 we observe the key result of the paper: We achieved a substantial reduction of the total energy cost of reefers at 44,68% . With other curves of electricity price, we achieved similar results. The results are very encouraging and much better than any other with real data or simulated data [17,31,14].

Table 1. Reduction of Total Energy Cost of Reefers.

Scenario	**Reduction of Total Cost**
This work, dummy scenario	0%
This work, moving average	2.15%
This work, with fuzzy	**44.68**%
Empirical Technique [52]	2.7-11%
MAS, with fuzzy [17]	16.6%
Peaks Reduction [31,14]	17%

In a recent work [17], with simulated data and a combined MAS architecture and fuzzy-logic based approach, simulated in MATLAB the operation energy cost of reefers was reduced by 16.6%. Several approaches were earlier investigated under the E-harbors project, such as the ports of Hamburg and Antwerp [52]. The exploitation of the reefers' flexibility led to estimated cost savings in the order of 5–7% and 2.7–11%, respectively. Others works of the same research team, using the same dataset with this paper [31,14], used an optimization algorithm to reduce the reefers' peak demands and achieved 17% cost savings. Hence, our combined MAS, implemented in JADE, and fuzzy-logic based approach performed much better compared to those approaches, and the obtained results are very satisfactory if compared to those of other approaches.

It is noted that the simulation time, in the scenario with cost under consideration, in a usual laptop, was about 300 sec. In contrast, in [17] a similar problem with the MAS being simulated in Matlab was carried out in 3562 sec (about 1h). The above results show the significance of using JADE and distributing computations over the different agents over Matlab [17] or Excel [31,14].

4 Conclusion

This paper shows that a cost effective, MAS-based, reefer system is an efficient solution for energy cost reduction at container terminals, as shown by our simulation results with real data. The complexity of the examined system and the necessity for a fast and reliable solution imposed the exploitation of a suitably designed MAS. The hierarchical structure of the proposed MAS captures the complexity of the examined system and the objectives of each agent type.

The way the agents interact to achieve their goals is presented in detail. The obtained results confirm the efficiency of the proposed method and indicate its potential to significantly reduce the operation cost of a commercial port.

We are currently working to extend this research by simulating all the components of the port micro-grid, such as cranes, plug-in electric vehicles, connected ships , widely known as “cold ironing”, wind-turbines and solar panels [23]. We expect that these components, each with its particular properties, will be seamlessly integrated into our architecture and protocols that we already developed using the ASEME methodology [48]. Moreover, we aim to apply this extended scenario with real port data. Finally, we aim to make this research, real-time.

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