Available online at: http://jurnal.untirta.ac.id/index.php/jiss

JOURNAL INDUSTRIAL SERVICESS

Industrial Engineering Advance Research & Application

eISSN 2461-0631

Multi-agent Based Modeling of Container Terminal Operations

Rully Tri Cahyono[1*]

[1]Departement of Industrial Engineering, Institut Teknologi Bandung
, Labtek III Matthias Aroef Building, Jalan Ganesa 10 Bandung 40132, Indonesia.

*rully@ti.itb.ac.id

ARTICLE INFO

Received: 2021-04-01
Revision: 2021-04-10
Accepted: 2021-04-20

Keywords:
Multi-agent Systems
Modeling
Container Terminal
Logistics

ABSTRACT

The existing research in container terminal operations systems have not yet fully depicted the entire operations processes. Moreover, these past works tend to use centralized static (linear programming-based) modeling methods to model the systems. A more suitable approach in distributed and changing environment of seaports is dynamical multi-agent systems (MAS). The existing methods (centralized and static) result in high terminal operations cost, which is a burden to the terminal operators. This research aims to utilize of MAS-based dynamics methods, which is also expected to cope the current drawbacks of the sequential communication methods. Eight agents that depict entities in the terminal are ship, port captain, terminal manager, stevedore, quay crane, straddle carrier, customs, and truck. The agents interact in the processes of ship arrival sequencing, determination of ship's service time and container picking. Based on the simulation result, agents' behavior is able to depict the real systems, and the current problem of the operations cost can be reduced up to 3% using our proposed methods. The agents tend to maximize profit in the early period and gradually decrease it to attain common agreement. The velocity of utility function attainment is about 2-5%, but because of the descend monotonic function, negotiation agreement is guaranteed to be attained. Moreover, we provide the detail MAS-based dynamical model as well as the proof that the consensus will be attained by the entire agents.

1. INTRODUCTION

The importance of container terminal operations has motivated the emergence of a lot of work in this field. Some of them are [7] and [8] which developed models for berth allocation policy optimization and quay crane scheduling. In addition, [6] has developed models for yard stowage policy optimization and yard crane scheduling. However, those models only acted partially, not wholly depicting the entire processes in the terminal. The partial models also emphasized that optimal decision can only be attained with the entire information obtained from various actors in the terminal. As an example, to make a berth allocation decision; ship's, yard's and gate's information have to be collected simultaneously. In practice, this action is nearly impossible because every actor is independent, therefore only partial access to the nearest neighbors (actors) is plausible.

The complexity of container terminal operations has limited researchers to work only in one or two sub-systems, i.e. seaside, transport, storage, and gate [3]. Where in reality, many decisions made in terminal cannot be separated from each other. For an instance, quay crane (QC) working times is known only after fixed schedule of internal trucks (IT) is released. Moreover, as has been extensively explain in [3], the models in [6], [7], and [8] are static, with emphasis on linear-programming (LP) techniques. The static modeling is not suitable with dynamic environment of container terminal operations. For instance, the actual berthing and stowage plans can differ from the original ones, because of some disruptions that make the pre-scheduled vessels arrive late to the designated seaport, or even cancel the operations completely.

Those weaknesses have successfully been covered by [1] which developed an integrated modeling of container terminal optimization in general seaport terminals and propose a solution based on a predictive control strategy. A set of dynamics of external inputs from ship arrivals, and external truck (ET) arrivals are considered. The ET come to terminal either to deliver or pick containers up. But, as have been mentioned before, the drawbacks of the models are the centralized decision-making process, which is not realistic in the actual setting. Distributed decision making is more suitable with container terminal operations [9].

The previous works also used sequential communication method. The method only accommodates the consideration of entities that directly taking part in the discussion and overrides the others entities' consideration that do not actively taking part in the discussion, but their performance is still affected by the decision. With this method, the decision is prone of trapped in local optimal area of the corresponding entities that directly takes part in the discussion. A forward-backward linkage negotiation method has been developed in [2] and [5]. The methods guarantee that the decision is well suited to the entire agents, whether those which actively takes part in discussion or in the other hand which only passively takes role, but their performance is affected by the decision concluded from the discussion.

We aim to develop distributed dynamical modeling of container terminal operations with multi-agent framework, which also be our first contribution. The dynamical container terminal operations are based on [1] and [3], while the MAS negotiation protocol is based on [2] and [5]. We modify the consensus algorithm and mathematically prove the convergence, which is also the second contribution of this paper. This is a significant improvement from the state-of-the-art works where usually optimality is only shown through a numerical/simulation experiment. With this mathematical approach, the algorithm can be further applied to the similar relevant systems, as has been shown in our previous work in [4].

This paper is organized as follows. After research motivation and contribution is presented in this section, the next section aims to give the readers the problem definition of the agent interaction processes. The negotiation protocol, the consensus algorithm and its mathematical proof is presented in the third section, and its subsequent numerical experiment is given in the fourth section. Finally, conclusion is given the fifth section.

2. AGENT INTERACTIONS

There are eight agents considered in the systems i.e. Ship Agent (SA), Port Captain Agent (PCA), Terminal Manager Agent (TMA), Stevedore Agent (SdA), Quay Crane Agent (QCA), Straddle Carrier Agent (SCA), Customs Agent (CA), and Truck Agent (TA). The interaction process is exemplified in Figure 1. Three main interaction processes exist i.e. ships arrival sequencing, ship's service time determination, and containers picking. The agent interactions are based on dynamical models of container terminal operations in [1] and [3].

2.1. Ship arrival sequencing interaction

Ships arrival sequencing period is conducted every 24 hours. The ships which is about to give their notice of arrival (NOA) to PCA. Based on the NOA, the PCA predicts the ships' arrival time which is later used to sequence their arrival with FIFO policy. The ships' data will be retrieved by the PCA to be distributed onto TMA, SdA and CA. It has to be understood that SA(s) are plural agents in the process of ships notification arrival. There are many SA(s) that are going to arrive to the port. In other hand, the SA is treated as single agent in the arrival time evaluation process to check whether the SA is late more than two hours or not. The same treatment happens when the PCA retrieves the ships' data.

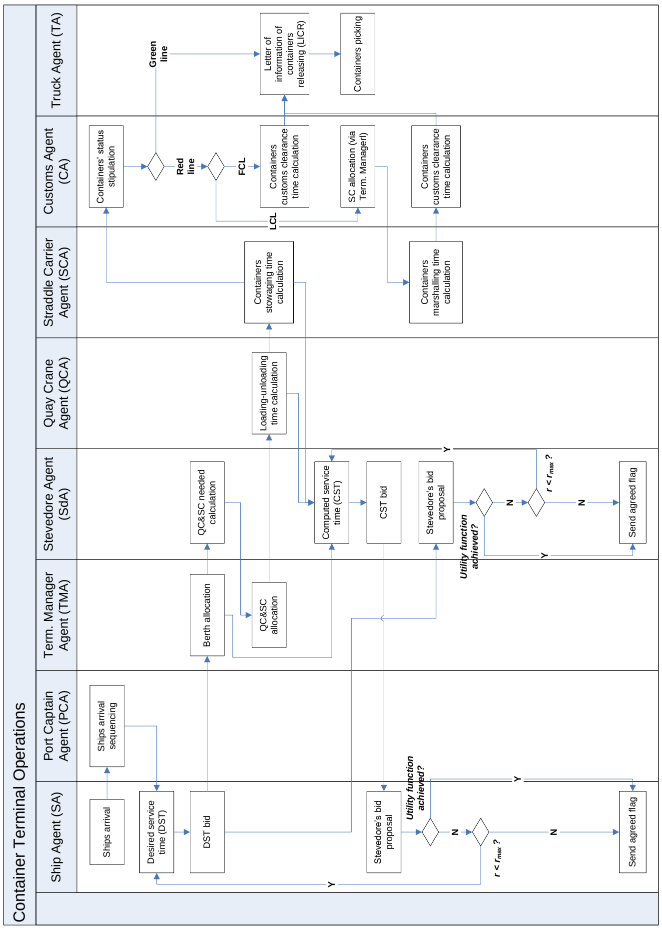


Figure 1. Agent interaction processes

The NOA is also sent to TA(s) which is representative of containers' owners. In the existing process, the NOA used by the TA(s) as an estimation of containers picking time in the terminal. But, the estimation is prone of inaccuracy because the ships arrival does not exactly delineate the real container picking time. When the containers are unloaded from the ships, the containers still have to do some customs clearance processes and also waiting in the container yard (CY), those instance are not well depicted in the NOA.

2.2. Ship's service time determination interaction

Interaction is commenced with a bid of Desired Service Time (DST) from SA to SdA which is calculated based on ship's Estimation of Time Departure (ETD). The SA will put an endeavor to maximize gap between ETD and DST which equals with minimization of cost that has to be beared by the ship during delays in terminal. The SdA response DST by computing Computed Service Time (CST). To be able in calculating CST, the SdA has to contact the corresponding agents i.e. TMA in quay allocation to ships berthing process, QCA in ships loading/unloading process, and SCA in CY marshalling process.

In determining the berthing points, the TMA conducts containers marshalling plan beforehand. The plan comprises of containers flow from every ship's bay that enter/exit to/from every CY block. The point is selected based on distance minimization between CY block with highest flow of entering/exiting containers with entire ship's possible berthing points. Ship's berthing time is summation of ship's transportation time from terminal's gate to the berthing point and berthing operation time. Simultaneously, the SdA calculates QCA and SCA needed and proposes to the TMA. Based on allocation from the TMA, the QCA loads/unloads containers in the ship and record the elapsed time. The SCA that operates in the CY also records the time needed for CY operations.

The total time of those three operations time are equal with Estimation of Time Service (ETS). The SdA tries to maximize gap between ETS and DST which is directly correlated with minimization of the terminal's operations cost. The longer time needed in operating the terminal utilities, the higher the cost incurred. Depends on the corresponding utility functions, the SA and the SdA negotiates until both of the utility functions attained or the negotiation itself has reached maximum round. The SdA acts as dominant-authorization agent of SA if no possible decision can be obtained from bids proposed by both agents. If deadlock happens, the system will use the last bid from the SdA. The same procedure used in the real system.

2.3. Ship's service time determination interaction

Ship's data obtained from bill of lading is used as a foundation for SA to stipulate customs categories of every container i.e. green line and red line. Containers are grouped in green line if they are considered as safety and need of no special treatment. The other extreme applies for red line which consists of next two categories i.e. Full Container Load (FCL) and Less than Container Load (LCL). CA will immediately be conducting clearances when the containers arrives at CY. Green line containers can pass the clearances, or its clearance time is zero. FCL red line containers are inspected in the CY. LCL red line containers are not inspected in the CY but have to be marshalled beforehand to the special area and unloaded. In another words, the LCL red line container is inspected based on its every freight, because one container may comprise of many freights with many owners. The CA then asks SdA to marshal and unload the containers. The SdA calculates the need of SCA to conduct the operations and proposes it to TMA. Based on the TMA's allocation, the SCA do the operations based on the plan conducted beforehand.

After the operations described above are fully completed, the CA can inspect every freight. In the case of LCL green line, customs clearance time is the CA's inspecting time add with the SCA's marshalling and unloading time. Immediately after the customs clearances finished, the CA issues Letter of Information of Containers Releasing (LICR) and send it to the corresponding TA(s). Based on the LICR, the TA(s) can extract information of containers picking time. With the mechanism, the TA(s) will come to the terminal to pick the containers only and if only the LICR received. The policy is to avoid a possible TA(s) waiting lines in the terminal because the containers to be picked have not yet completed their customs clearances.

3. NEGOTIATION PROTOCOL AND CONSENSUS ALGORITHM

Communication which happens among the modeled terminal's entities uses negotiation concept of the monotonic concession protocol from [2] and [5]. To overcome gaps of negotiation models from Wooldridge those two papers, forward-backward linkage is considered in this paper, which framework can be found in [4]. The complete negotiation protocol is as follow:

- Negotiation lasts for some discussion rounds.
- Agreement is tried to be reached by the discussed agents from the very first round based on the submitted proposals.
- Agreement is reached if by transaction δ_1 and δ_2 that is offered by every agent, utility y_1 $(\delta_2) \geq y_1$ (δ_1) and y_2 $(\delta_1) \geq y_2$ (δ_2).
- If agreement is attained, transaction value is stipulated by the value agreed by the two sides of agents which are discussing.
- If the transaction result between two agents have impact to performance of the other agents, the result has to be tested to the other corresponding agents to get mutual decision.
- If no agreement is reached, the discussion goes on to round $u + 1$, in which every agent cannot make bid that gives lower utility to the other agents compare to the utility in the round u.
- If no agreement is reached between two agents in the round $u > 0$, negotiation is concluded with the last transaction as an agreement. Decision is taken from the agent's bid that has higher authority per hierarchy.

The next steep is to provide the mathematical analysis for the negotiation protocol. We define the problem presented in this paper as follows.

Definition

Let $\mathbf{G}_n$ be the undirected graph which associated n followers, labeled as agents 1 to n. In our case, the agents are the eight agents in the container terminals. Let $\mathbf{A}_n = [a_{ij}] \in \mathbf{R}^{nxn}$ and $\mathbf{L}_n \in R^{nxn}$ be, the adjacency and symmetrical Laplacian matrix, respectively, which associated with $\mathbf{G}_n$. We assume that in addition to the n followers, there exists a leader, labeled as agent $n + 1$.

Let $\mathbf{G}_{n+1}$ be the directed graph associated with agents 1 to n+1. Let $\mathbf{H} = \mathbf{L}_n + \mathrm{diag}(a_{1(n+1)}, \ldots, a_{n(n+1)})$, where diag denotes a diagonal matrix with these diagonal entries.

A MAS model is best modeled in network, which relevant matrix representation [10]. In this case, the interaction is the communication among agents. How to handle the communication is provided with the negotiation protocol as abovementioned. To show that the protocol will lead to stable (converge), condition, [2], [5], and [10] has proposed that H in the Definition 1 has to be symmetric positive definite. To make such mathematical proof, we use the framework from our previous work in [4].

Proof

Given our problem, which represent the dynamics of each agent as follow

$$\dot{\boldsymbol{\xi}}_i = \boldsymbol{\xi}_i, \;\; \dot{\boldsymbol{\xi}}_i = \boldsymbol{u}_i, \;\; \boldsymbol{i} = \mathbf{1}, \ldots, \boldsymbol{n} \quad (1)$$

Consider a consensus algorithm for (1) as

$$\boldsymbol{u}_i = -\left[\sum_{j=1}^{n} \boldsymbol{a}_{ij}\left(\boldsymbol{\xi}_i - \boldsymbol{\xi}_j\right)\right] - \boldsymbol{\alpha}\boldsymbol{\xi}_i, \;\; \boldsymbol{i} = \mathbf{1}, \ldots, \boldsymbol{n} \quad (2)$$

where a_{ij} is the element of a constant adjacency matrix $\mathbf{A}_n$ and α is a position scalar. Following the procedure in [4], let $\boldsymbol{\xi} \triangleq \left[\boldsymbol{\xi}_1^T, \ldots, \boldsymbol{\xi}_n^T\right]$. By applying (2) to (1), we can rewrite the original problem as

$$\begin{bmatrix} \dot{\boldsymbol{\xi}} \\ \dot{\boldsymbol{\xi}} \end{bmatrix} = (\boldsymbol{\Theta} \otimes \mathbf{I}_m) \begin{bmatrix} \dot{\boldsymbol{\xi}} \\ \boldsymbol{\xi} \end{bmatrix} \quad (3)$$

$$\boldsymbol{\Theta} = \begin{bmatrix} \mathbf{0}_{nxn} & \mathbf{I}_n \\ -\mathbf{L}_n & -\boldsymbol{\alpha}\mathbf{I}_n \end{bmatrix} \quad (4)$$

The eigenvalues of θ in (4) can be found through its characteristic polynomial

$$\det(\boldsymbol{\lambda}\mathbf{I}_{2n} - \boldsymbol{\Theta}) = \mathbf{0}$$

$$\det\left(\begin{bmatrix} \boldsymbol{\lambda}\mathbf{I}_n & -\mathbf{I}_n \\ \mathbf{L}_n & \boldsymbol{\lambda}\mathbf{I}_n + \boldsymbol{\alpha}\mathbf{I}_n \end{bmatrix}\right) = \mathbf{0} \quad (5)$$

$$\det(\boldsymbol{\lambda}\mathbf{I}_n(\boldsymbol{\lambda}\mathbf{I}_n + \boldsymbol{\alpha}\mathbf{I}_n) + \mathbf{L}_n) = \mathbf{0}$$

Following the reformulation in (5), we further note that

$$\det(\boldsymbol{\lambda}\mathbf{I}_n + \boldsymbol{\alpha}\mathbf{I}_n) = \prod_{i=1}^{n}(\boldsymbol{\lambda} - \boldsymbol{\mu}_i) \quad (6)$$

By comparing (5) and (6), we obtain

$$\det(\boldsymbol{\lambda}\mathbf{I}_n(\boldsymbol{\lambda}\mathbf{I}_n + \boldsymbol{\alpha}\mathbf{I}_n) + \mathbf{L}_n) = \prod_{i=1}^{n}(\boldsymbol{\lambda}(\boldsymbol{\lambda} + \boldsymbol{\alpha}) - \boldsymbol{\mu}_i) = \mathbf{0} \quad (7)$$

According to (7), subsequently we can find the roots of (5) as follow:

$$\boldsymbol{\lambda}_{i+/-} = \frac{-\boldsymbol{\alpha} \pm \sqrt{\boldsymbol{\alpha}^2 + 4\boldsymbol{\mu}_i}}{\mathbf{2}} \quad (8)$$

Proposition

The network of agents in the container terminal, which is represented by $\mathbf{G}_n$ has a directed spanning tree.

Proof

Based on the proposition, and by noting to Lemma 2.1 in our previous work in [4], it follows that $\mathbf{L}_n$ has exactly one zero eigenvalue. Then, $-\mathbf{L}_n$ has at least one zero eigenvalue and all the other eigenvalues of $-\mathbf{L}_n$ have negative real parts. Then, θ has at least two eigenvalues.

Without losing generality, we let $\mu_i = 0$ and

$$\boldsymbol{\lambda}_{1+} = \frac{-\boldsymbol{\alpha} + \sqrt{\boldsymbol{\alpha}^2}}{\mathbf{2}} = \mathbf{0} \quad (9)$$

$$\boldsymbol{\lambda}_{1-} = \frac{-\boldsymbol{\alpha} - \sqrt{\boldsymbol{\alpha}^2}}{\mathbf{2}} = -\boldsymbol{\alpha} \quad (10)$$

If the other eigenvalues of L_n are $\mu_i < 0$, then for any $\alpha > 0$, we obtain

$$\mathrm{Re}\left(\boldsymbol{\lambda}_{i+/-}\right) = \mathrm{Re}\left(\frac{-\boldsymbol{\alpha} \pm \sqrt{\boldsymbol{\alpha}^2 + 4\boldsymbol{\mu}_i}}{\mathbf{2}}\right) < \mathbf{0} \quad (11)$$

Based on (11), all other eigenvalues of θ have negative real parts. Based on this and the aforementioned condition, consensus is achieved using (2) for (1) if only if $\mathbf{G}_n$ has a directed spanning tree and $\alpha > 0$.

We introduce $\mathbf{1}_n$ and $\mathbf{0}_n$ as the two matrices whose the entire elements are 1 and 0, respectively. We have $\mathbf{L}_n\mathbf{1}_n = 0$ and it follows that is $[\mathbf{1}\boldsymbol{n}^T, \mathbf{0}\boldsymbol{n}^T]^T$a right eigenvector of θ corresponding with zero eigenvalue. This condition implies that span is $[\mathbf{1}\boldsymbol{n}^T, \mathbf{0}\boldsymbol{n}^T]^T$contained in kernel of θ. Then it follows

$$\begin{bmatrix} \dot{\boldsymbol{\xi}}(\boldsymbol{t}) \\ \boldsymbol{\xi}(\boldsymbol{t}) \end{bmatrix} = \mathrm{span}\left(\begin{bmatrix} \mathbf{1}_n \\ \mathbf{0}_n \end{bmatrix} \otimes \boldsymbol{\gamma}\mathbf{1}_m\right), \;\; \boldsymbol{\gamma} \in \mathbf{1}_m \quad (12)$$

The condition in (12) follows as t goes to infinity, where t is the discrete or continuous time as our models are the dynamical ones based on framework in [3].

Based on (12), we complete the proof that the consensus equilibrium is given by $\boldsymbol{\xi}^* = \boldsymbol{\gamma}, \boldsymbol{\gamma} \in \mathbf{R}$ and $\boldsymbol{\xi} = \mathbf{0}$, where the consensus algorithm is given by

$$\boldsymbol{u}_i = -\sum_{j=1}^{n} \boldsymbol{a}_{ij}\boldsymbol{\phi}\left(\boldsymbol{\xi}_i - \boldsymbol{\xi}_j\right), \;\; \boldsymbol{i} = \mathbf{1}, \ldots, \boldsymbol{n} \quad (13)$$

4. NUMERICAL EXPERIMENT

After the interactions are completely modeled and also mathematically proven in the previous section, the next step is analysis to extract phenomenon from model development and testing stages. Analysis comprises of two parts i.e. result and performance analysis. We obtained the data needed for the simulation from our observation in the third terminal of Port of Tanjung Priuk, Jakarta. The observation is done in the period of September to October 2020.

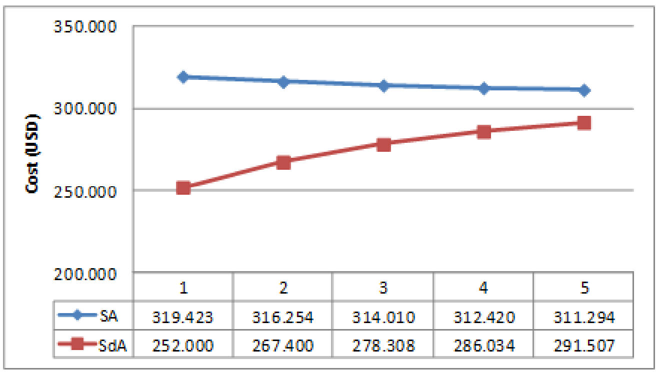
The average ship inter-arrival times is 8 hours and 21 minutes. The average ship loads are 1,282 TEU (twenty-feet equivalent unit). There are 2 QC in the terminal, which we assume the same operational speed of 20 container (TEU) per hour, to simplify the simulation. There are two storage area in the CY, namely yard blocks, each is for incoming (import) and outgoing (export), respectively. In each block, there area two YC, with operational speed of 12 TEU/hour. To transport the containers between seaside (QC) and storage (YC), the terminal use 10 transporters (trucks) with the same operational specification.

Based on the terminal specification, we simulate the terminal operations systems using MAS models and algorithm proposed in Section 3. We randomize the parameters using uniformly random generators. We use five rounds, where 10 datasets are used in each round. The simulation is done with Matlab R2019B, in a i5 computer, with 8 GB RAM, and 6 MB cache microprocessors.

4.1. Result analysis

Result analysis discusses costs incurred by the corresponding agents in every interaction process. Cost is one of performance criteria beside the other criteria such as SC's travel distances. Costs beared by the SA and the SdA during ship's service time determination interaction is presented in Figure 2. In this figure, five round of simulation is presented.

As abovementioned, each round is the average from ten trials. The average to simulate one trial is 26,6 seconds. Round 1 is the existing policy in the terminal operations, while round 2 to 5 use our proposed MAS models and algorithm, where as the round increases, the MPC horizon parameter from our previous work in [3] and [4] is also increases. We can see in the round 5, there is cost reduction around 2,5%. Although seem marginal, this equals with around 8,000 USD per day, which is a significant cost reduction for the terminal operations.



	1	2	3	4	5
SA	319.423	316.254	314.010	312.420	311.294
SdA	252.000	267.400	278.308	286.034	291.507

Figure 2. SA and SdA operations costs

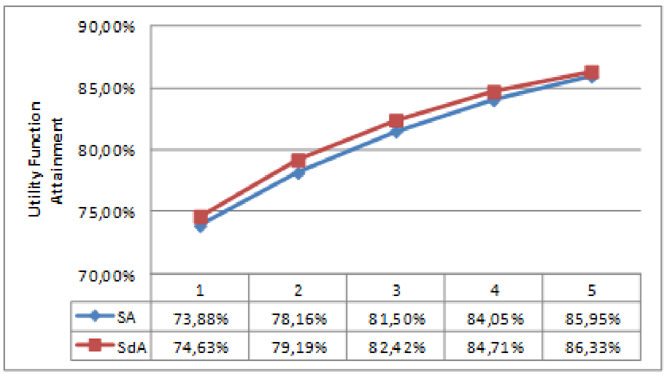
The SdA is regarded as terminal operators which is responsible in generating income to the container terminal. With this terminology, every profit for terminal operator is difference between cost paid by the SA and cost paid by the SdA. From the terminal operator perspective, cost incurred by SA is equal with revenue for the SdA. The SA cost component is Terminal Handling Cost (THC) and ship cost during delays in the terminal. While the SdA cost component is container terminal operating cost. The SdA's profit diminishes as the negotiation round runs. This phenomenon is well-suited with the real system where in beginning terminal operators want to get profit as high as possible. But, the terminal users, in this term the SA do not willing to because some added costs have to be beared. Thus, it can be understood that the SA's cost curve continues to go down. While in the other hand, the SdA's cost curve is positive monotone that indicates if cost that is charged to the SA in the beginning turns into the SdA's charge.

4.2. Performance analysis

It is discussed in [2] and [5] that one of performance indicators that can be employed to evaluate multi-agent system model's performance is by analyzing how fast is every negotiating agent in achieving its utility function. Utility function attainment for the SA and the SdA is exemplified in Figure 3. Both of the SA and the SdA have positive monotone utility functions as the negotiation round runs. It means that model has been consistent to achieve utility function albeit 100% utility function cannot be reached during the maximum five negotiation round. But, with the attainment graphic, which is constantly ascend, SA and SdA will attain their utility functions with some additional negotiation rounds. Non-positive monotone utility function attainment is somewhat avoided in the MAS model because the instance may trigger negotiation process ends in no-solution. The SA and the SdA have the same velocity pattern i.e. fast in the beginning and continues to descend in the next rounds. Velocity in the last round is approximately 2% and this value can still be accepted because as the round goes on, utility function value base still ascends. That means utility function expectation value in the next round is still big enough.

5. CONCLUSION

We have developed a dynamical MAS-based model of container terminal operations. From the real systems perspective, the MAS model has successfully included customs clearance process to fill the gap of the past research. The model is still based on MAS decentralized concept because it is proven to be effective in modelling complex processes as exists in the export/import container terminal operation system.



	1	2	3	4	5
SA	73,88%	78,16%	81,50%	84,05%	85,95%
SdA	74,63%	79,19%	82,42%	84,71%	86,33%

Figure 3. SA and SdA utility function attaintment

We have proposed a MAS consensus algorithm. We have also mathematically proven the algorithm to be converges as the time goes to infinity. The proofs can serve as the basis of other application in the similar systems. Based on the simulation result, agents' behavior is appropriate with the real systems. The agents tend to maximize their profit in the early period and decrease it along with the negotiation process to attain a common agreement. The velocity of utility function attainment is about 2-5%, but because of the descend monotonic function, negotiation agreement is guaranteed to be attained. The customs clearance is more effective than the existing system because the trucks can only come to the terminal when the corresponding containers have been completely inspected. In addition, the communication method is also able to include consideration from the entire corresponding agents in decision making, not only for agents who are directly involved in discussion.

In the next steps of the research, it is suggested to consider the entities such as containers empty depot, forwarder, finance institutions and government in the examined system. In the real system, those entities are inseparable and could make great impact to the whole system's performance.

REFERENCES

[1] A. Alessandri, C. Cervellera, and M. Gaggero, "Predictive Control of Container Flows in Maritime Intermodal Terminals," *IEEE Transactions on Control Systems Technology*, 2013, doi: 10.1109/TCST.2012.2200680.

[2] V.D. Blondel, J.M. Hendrick, A. Olshevsky, and J.N. Tsitsiklis, "Convergence in Multiagent Coordination, Consensus, and Flocking," *Proceedings of the 44th IEEE Conference on Decision and Control*, 2005, doi: 10.1109/CDC.2005.1582620.

[3] R.T. Cahyono, E.J. Flonk, and B. Jayawardhana, "Discrete-Event Systems Modeling and Model Predictive Allocation Algorithm for Integrated Berth and Quay Crane Allocation," *IEEE Transactions on Intelligent Transportation Systems*, 2020, doi: 10.1109/TITS.2019.2910283.

[4] R.T. Cahyono and B. Jayawardhana, "On the Optimal Input Allocation of Discrete-Event Systems with Dynamic Input Sequence," *Proceedings of the 58th IEEE Conference on Decision and Control*, 2019, doi: 10.1109/CDC40024.2019.9029828.

[5] X. David-Henriet, L. Hardouin, J Raisch, and B. Cottenceau, "Model Predictive Control for Discrete Event Systems with Partial Synchronization," *Automatica*, 2016, doi: 10.1016/j.automatica.2015.12.006.

[6] R. Delgado, R.M. Jensen, and K. Janstrup, "A Constraint Programming Model for Fast Optimal Stowage of Container Vessel Bays," *European Journal of Operational Research*, 2012, doi: 10.1016/j.ejor.2012.01.028.

[7] M.M. Golias, M. Boile, and S. Theofanis, "A Lamda-Optimal Based Heuristic for the Berth Scheduling Problem," *Transportation Research Part C*, 2010, doi: 10.1016/j.trc.2009.07.001.

[8] H-P. Hsu, "A HPSO for Solving Dynamic and Discrete Berth Allocation Problem and Dynamic Quay Crane Problem Simultaneously," *Swarm and Evolutionary Computation*, 2016, doi: 10.1016/j.swevo.2015.11.002.

[9] M.E.H. Petering and K.G. Murty, "Effect of Block Length and Yard Crane Deployment Systems on Overall Performance at A Seaport Container Transshipment Terminal," *Computers & Operations Research*, 2009, doi: 10.1016/j.cor.2008.04.007.

[10] P.J.G. Ramadge and W.M. Wonham, "The Control of Discrete-Event Systems," *Proceedings of the IEEE*, 1989, doi: 10.1109/5.21072.