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OPTIMISING WASTE MANAGEMENT COLLABORATION PROCESSES USING HYBRID MODELLING

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Abstract
The high amount of hazardous medical waste involves high risks, so optimising waste management processes is crucial. Some research proposes hybrid modelling that combines simulations and operation research approaches, and most hybrid modelling methods focus on optimising waste transport routes. This paper proposes hybrid modelling to optimise the number of workers with minimum asynchronous waiting time (*AWT*) and activity costs based on waste management collaboration processes. Hybrid modelling consists of an integrated discrete-event simulation, agent-based simulation and improved MCDM methods (MOORA and COPRAS). The cases of waste management processes under normal and overload conditions verify the performance of the proposed hybrid modelling. Improved MCDM methods save 27 % of MCDM processing time. The *AWT* and activity cost under normal condition using the hybrid modelling decreased by 38 % and 22 %, respectively. Hybrid modelling can minimise 74 % *AWT* and 31 % activity cost compared to the actual model under an overload condition. MOORA is better when reducing activity cost, and COPRAS is better when minimising *AWT*.
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Key Words: Agent-Based Simulation, Collaboration Process, Discrete-Event Simulation, Hazardous Waste Management, Multi-Criteria Decision-Making, Time-Cost Optimisation

1. INTRODUCTION

Based on the WHO report 2022 [1], millions of pounds of medical waste due to the Covid-19 spike have placed enormous pressure on healthcare waste management systems worldwide. Hazardous medical waste contributes a small portion of the amount of medical waste, but has a high-risk impact. Hazardous medical waste contains infectious microorganisms that endanger patients, health workers and the surrounding community [2, 3]. The lack of a waste management system is a challenge for the waste management sector [4], improvement in the medical waste management system is urgently needed. This is where simulation and optimisation methods can play an important role [5].

Some studies have contributed to analyse waste management processes. Kummer et al. [6] implemented hybrid simulation that combined agent-based simulation (ABS) and discrete-event simulation (DES) to optimise waste management system. Ding et al. [7] analysed the impact on the environment of waste management using hybrid simulations that integrated system dynamics (SD), ABS, and DES. Alsobky et al. [8] proposed a hybrid modelling that combined a simulation model and Genetic algorithm to optimise waste collection. Fajar and Sarno [9] proposed a hybrid modelling (a combination of ABS and MCDM methods) to determine the optimal number of agents according to the *AWT* and cost parameters. Liu and Yao [10] designed a model to simulate the medical waste classification management system and medical waste recycling processes using DES. Geetha et al. [11] proposed operation research (OR), that is, fuzzy MULTIMOORA as a multicriteria decision-making (MCDM) method, to evaluate waste disposal stages. Zhao et al. [12] optimised the vehicle and route of infectious waste management using the proposed biobjective approach. Cao et al. [13] optimised the location and transport strategies of medical waste using an interval-based robust bilevel mixed-integer programming model. Many studies implemented hybrid simulation, hybrid modelling [14], or OR approaches; however, no research implements hybrid modelling that integrates hybrid simulation and OR approaches to analyse or optimise waste management. Furthermore, most studies focus on optimising waste treatment transport routes. This study suggested a hybrid modelling (hybrid simulation and MDCM approach, which are MOORA and COPRAS methods) to optimise waste management processes with the optimal number of workers considering time and cost.

This study designed a proposed simulation based on a medical waste collaboration process model. The process model describes the collaboration processes [15-20] between waste operation processes and documentation operation processes. DES [21-23] models the flow of activities, and many DES tools have a split operator to run multiple processes, such as waste operation and documentation operation, simultaneously. A DES, including a split operator, can implicitly simulate collaboration processes; however, the DES cannot explicitly display the entire flow of each process because these processes have merged into one. Suppose a collaboration model is simulated with several discrete-event simulations (DESs), where a DES represents a process. In that case, links between those DESs are needed to simulate the interaction between processes in the collaboration model.

Time and cost are essential and common optimisation parameters. Total processing time can be reduced by minimising waiting time. The waiting time occurs for several reasons. First, a worker (agent) does not carry out any activities because they are resting or their supporting devices are broken. Second, a worker handles a previous case of an activity when a new case arises. The second reason is asynchronous waiting time (*AWT*) [9, 24]. The waiting time that occurs in a simulation model is *AWT*. Fajar and Sarno [9] determined the optimal number of agents for the entire process, so the optimal number of agents will be divided equally for each activity. The method by Fajar and Sarno will not give optimal results in a case study with a high difference in *AWT* between several activities due to the emergence of an excess number of agents in activities with low *AWT*. The excessive number of agents causes cost overruns.

Taking into account the previous explanation, the use of hybrid modelling to optimise waste management processes based on a collaboration process model has not yet been carried out. In addition, hybrid modelling was applied to minimise asynchronous waiting time and cost to a global process, not specific to each activity. These motivations became the basis of authors for compiling this study. In short, the contribution of this study is the following: (1) a novel hybrid modelling (an integrated discrete-event simulation, agent-based simulation and improved MCDM methods) to determine the optimal number of workers in waste management collaboration processes; (2) a combination of discrete event simulation and agent-based simulation to simulate collaboration processes; (3) automatic calculations of *AWT* and activity cost in the proposed simulation; and (4) improved MCDM methods by adding rules for implementing MCDM methods based on activity relationships to minimise processing time of MCDM methods.

The remainder of this paper is structured as follows. Section 2 discusses preliminary methods. Section 3 details the case study and the proposed hybrid modelling. Section 4 explains the optimisation result in the experiment cases, which are normal and overload conditions. Finally, Section 5 concludes this work.

2. PRELIMINARY

2.1 Asynchronous waiting time

Fig. 1 is a flow model of two cases of two activities carried out by two workers (agents) to illustrate the difference between waiting time and asynchronous waiting time. Based on Fig. 1, the asynchronous waiting time *(AWT*) is part of the waiting time where *AWT* occurs because

Agent 2.1.1 has not finished the first case of Activity 2.1. The simulation model overrides waiting time due to external conditions (damage of support systems or personal desire of workers not to start work), so the waiting time in a simulation model reflects AWT.

AWT_a (AWT of activity a) is obtained by subtracting the start time execution of activity a (STE_a) with the arrival time of message from a previous activity (AT_{a-1}). For the initial activity, AT_{a-1} is arrival time of the case. AWT_a is calculated using Eq. (1), where n is the number of cases.

$$AWT_a = \sum_{i=1}^{n} (STE_{a_i} - AT_{a-1_i}) \quad (1)$$

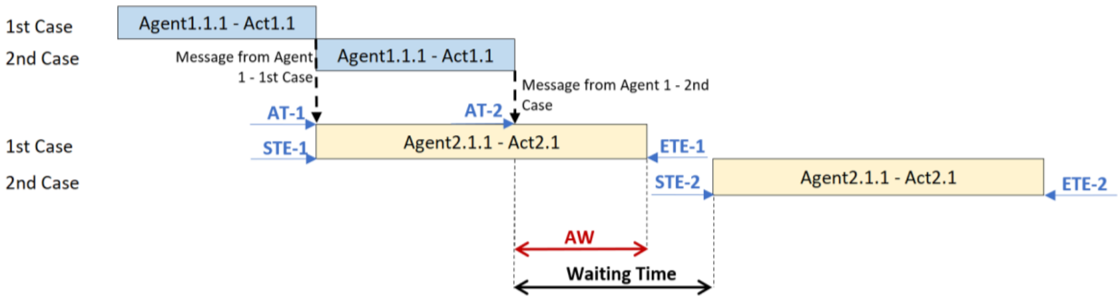

Figure 1: Asynchronous waiting time.

2.2 Multi-criteria decision making (MCDM)

MCDM is one method that can provide the best and worst solutions with many conflicting alternative choices [25]. This study includes methods in MCDM, using MOORA and COPRAS. MOORA has been shown to be applicable in various problems such as the selection of machine gear material [25], decision-making in business analysts [26], and the decision-making of logistics outsourcing [27]. COPRAS has been shown to be able to solve problems such as selecting data [28] and determining optimal parameters of processes [29-31]. The MOORA steps used in this paper are as follows.

1. Create matrix M_{mn} to store all alternatives from the DES simulation (m) based on the criteria n.
2. Calculate the denominator of the n value of the criteria n value based on M_{mn} using Eq. (2) and normalise each value in M_{mn} with d_nM.

$$d_nM = \sqrt{\sum_{i=1}^{m} (x_{in})^2} \quad (2)$$

3. Give weight to normalisation M_{mn} using Eq. (3) for each criterion to be minimised. Optimisation is calculated on Eq. (4).

$$S_- = \sum_{j \in \Omega_{min}} w_j r_{mj} \quad (3)$$

$$Q_iM = -S_- \quad (4)$$

The COPRAS stages have differences in determining the denominator and optimisation. Determining the denominator and optimisation can be seen in Eqs. (5) and (6).

$$d_nC = \sum_{i=1}^{m} x_{in} \quad (5)$$

$$Q_iC = \frac{min_{(S_-)} \sum_{i-1}^{m} S_-}{S_- \sum_{i=1}^{m} \frac{min(S_-)}{S_-}} \quad (6)$$

3. MATERIAL AND METHOD

3.1 Case study: Medical waste management

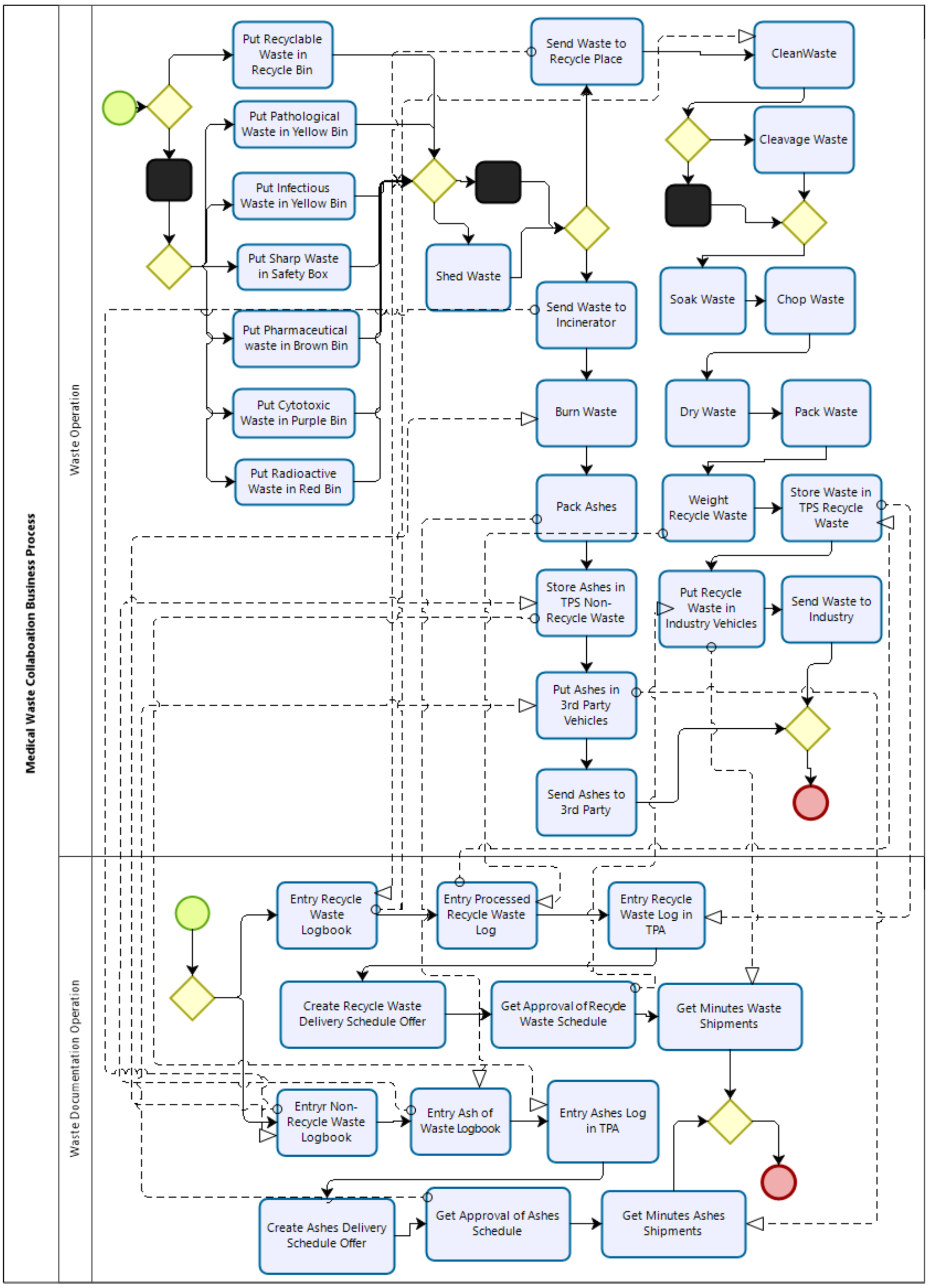

Figure 2: Medical waste collaboration process model.

The case study is the medical waste management processes of a hospital, which are divided into waste operation processes and waste documentation operation processes. Waste operation processes handle seven types of waste: recyclable waste, pathological waste, infectious waste, sharp waste, pharmaceutical waste, cytotoxic waste, and radioactive waste. Recyclable waste is cleaned and chopped before being sent to the waste and recycling industry. Other wastes are incinerated, and their remaining ashes are carried out by third parties (environmental waste management services). Radioactive waste decays for 6 hours before being incinerated to remove radiation. Waste documentation operation processes are creating logs of treated wastes and documents for the waste and recycling industry or third parties. The categories of waste in the log are only two: non-recyclable waste and recyclable waste. Six types of waste, other than recyclable waste, are included in non-recyclable waste.

Workers in waste operation processes interact with workers in waste documentation operation processes in treating wastes and vice versa. An example of the interaction of those processes is incinerator workers burn waste after workers of waste documentation create an arrival log of non-recyclable waste. This study constructed a waste management collaboration process model (Fig. 2) to describe waste operations processes, waste documentation processes and interactions between those processes. The blue rectangles and the dotted arrows in the collaboration process model indicate activities and process interactions, respectively.

In this study, the number of medical waste as the number of simulation cases was calculated based on the number of patients with Covid-19 infection in Surabaya in 2020 [32]. This study retrieved the data in March – April 2020 [32] as input to the simulation during normal conditions. The data in July – August 2020 was chosen as the data during the overload condition because there was a marked increase in the number of Covid-19 sufferers in Surabaya in July – August 2020. The amount of medical waste for each type of waste (W) on t day (n_{W_t}) was calculated according to Eq. (7). A Covid-19 patient generates approximately 2 kg [33], so the amount of medical waste per day was double the number of Covid-19 patient per day (I_t). Infectious waste contributed about 42 % of the total wastes [33]. According to the percentage of infectious wastes, 42 % of n_{W_t} were infectious wastes and the remaining 58 % were equally divided into other types of waste (approximately 9 %). In the simulation, there were three (3) arrival times for wastes per day: 07:00, 10:00, and 13:00. The number of wastes per day was divided equally for each session.

$$\begin{cases} n_{W_t} = (I_t \times 2 \times 42\ \%), & \text{if } W = \text{Infectious Waste} \\ n_{W_t} = (I_t \times 2 \times 9\ \%) & \text{otherwise} \end{cases} \tag{7}$$

3.2 Methodology

The main steps of the novel hybrid modelling are described in Fig. 3. This study constructed a hybrid modelling that integrated DES, ABS, and MCDM approaches. DES is a framework for modelling systems with discrete events, such as the arrival of waste, and simulating a series of processes that include activities with defined sequencing rules [34]. This study constructed two DESs to simulate waste operations and waste documentation processes. In addition, ABS models the behaviour patterns of agents or workers performing activities and simulates the integration between these agents [34]. In this paper, ABS is used to model interactions between agents in the Waste Operations DES and agents of the Waste Document Operations DES. The next step is that this study runs the simulations and obtains *AWT* and activity costs using the proposed automated calculation. Furthermore, this study applied improved MCDM methods to determine the optimal *AWT* and activity costs. The novel hybrid modelling was evaluated using the number of wastes under normal conditions and those under overload conditions.

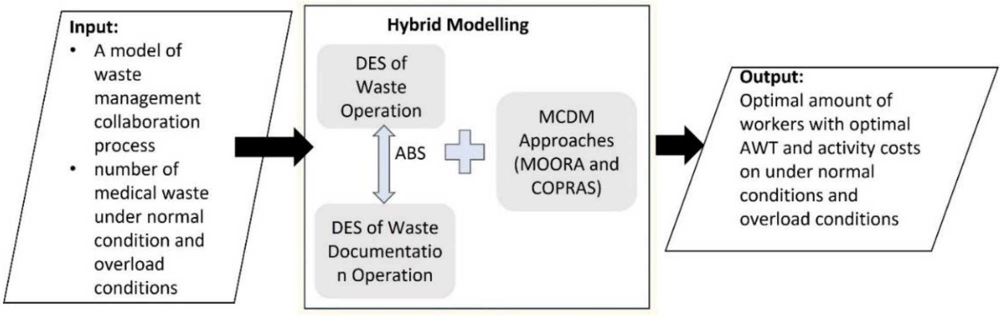

Figure 3: Framework of proposed hybrid modelling.

The first step of the proposed method is building the hybrid simulation (shown in Fig. 4). In the hybrid simulation, DES of Waste Operation and DES of Waste Documentation Operation are used to simulate detailed processes of each operation. Meanwhile, ABS simulates interactions between these DESs. A DES of Waste Operation has 25 activities, and a DES of Waste Documentation Operation has 12 activities (symbolised by dark blue rectangles in Fig. 4). This study indicates the processing time of each activity in DESs according to Table I. There are states in the ABS, and each state manages an interaction between DESs. Each state will manage the interaction according to the dotted arrow in the collaboration process model in Fig. 2. Fig. 4 presents two states of ABS to illustrate the interaction. First, the states in ABS will check whether the process on activities of a DES as the sender of message has been completed or not. If the process on the activity has been completed, then the states of the ABS will change the hold (symbolised by a red circle with a white centre line) status to true so that the activity as the recipient of the message on another DES can be executed. For example, stateSC1 changes the hold status on the DES of the Waste Documentation Operation to true after the waste in the *sendWasteToRP* activity is executed on the DES of the Waste Operation. The document can be processed to *entryRWProcessedLog* activity after the hold is true.

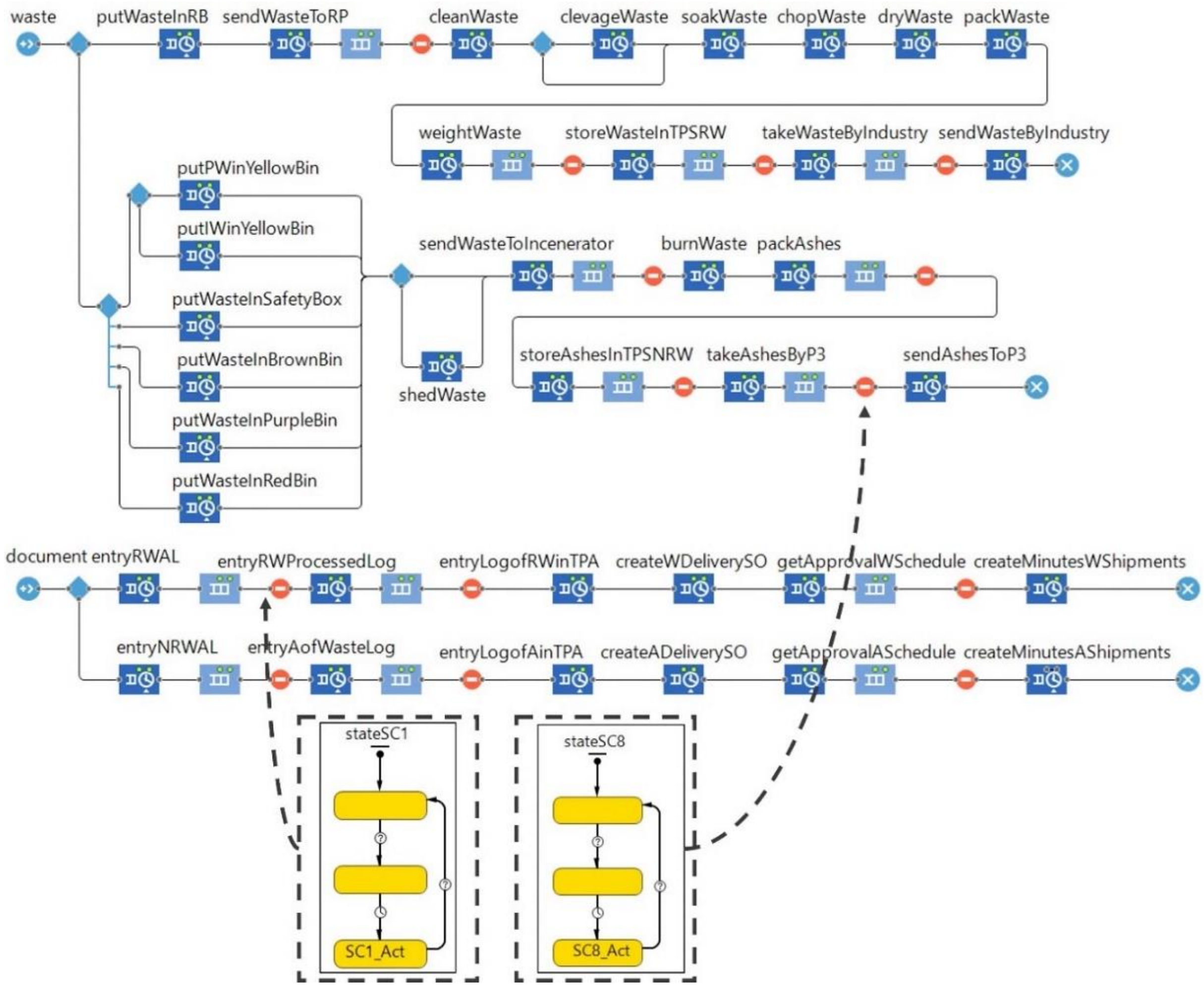

Figure 4: Proposed hybrid simulation.

In addition to building the hybrid simulation, this study develops automatic calculation methods of *AWT* and activity cost that are coupled with the hybrid simulation, so the total *AWT* and activity cost are directly obtained in one application. The proposed methods are described in Algorithm 1 and Algorithm 2 respectively.

Table I: Parameters used in DES of Waste Operation and DES of Waste Documentation Operation.

Activities	**Processing time**
DES of Waste Operation	
putWasteInRB, putWasteInSafetyBox, putWasteInBrownBin, putWasteInPurpleBin, putWasteInRedBin, dryWaste, takeWastebyIndustry, takeAshesByP3	5 minutes
sendWasteToRP	14 minutes
cleanWaste, clevageWaste, chopWaste, packWaste, weightWaste, burnWaste, packAshes, sendWasteToRP, sendWasteToIncenerator	1 minutes
soakWaste, putPWInYellowBin, putIWInYellowBin	10 minutes
storeWasteInTPSRW, storeAshesInTPSNRW	7 hours
shedWaste	6 hours
sendWasteByIndustry, sendAshesToP3	2 hours
DES Waste Documentation Operation	
entryRWAL, createWDeliverySO, createMinutesWShipments, entryNRWAL, createADeliverySO, createMinutesAShipments	5 minutes
entryRWProcessedLog, entryLogofRWinTPA, entryAofWasteLog, entryLogofAinTPA	10 minutes
getApprovalWSchedule, getApprovalASchedule	30 minutes

Algorithm 1. Automatic calculation of AWT

Input: Start time of activity a of case i (STE_{a_i}), Arrival time of message from activity $a-1$ of case i (AT_{a-1_i})

Output: $totalAWT$

for i = 0 to the last case of simulation **do**
    for a = 0 to the last Activity **do**
        AWT_{a_i} is calculated based on Eq. (1). $totalAWT_a \leftarrow totalAWT_a + AWT_{a_i}$
    end for end for
return $totalAWT$

Algorithm 2. Automatic calculation of Activity Cost

Input: Start time of activity a of case i (STE_{a_i}), End time of activity a of case i (ETE_{a_i}), Worker salary of activity a (C_{r_a}), Total resource of activity a (n_{r_a}), Cost of used equipment in activity (C_{a_e}), Total AWT of activity a (AWT_a), Cost of AWT of activity a ($CAWT_a$)

Output: *totalCost*

for i = 0 to the last case of simulation **do**
    for a = 0 to the last Activity **do**
        $Cost_{a_i}$ is calculated based on Eq. (10). $totalCost_a \leftarrow totalCost_a + Cost_{a_i}$
    end for end for
return $totalCost$

The automatic AWT calculation method fetches the start time of an activity (a) and the arrival time of the message from the previous activity (a-1) from every executed case in the hybrid simulation. Subsequently, the method implements Eq. (1) to obtain AWT for each activity (AWT_a). The AWT of each activity is stored in a list of AWT arrays called $totalAWT$. The automatic activity cost calculation method retrieves several parameters from the hybrid simulation and implements Eq. (10) to obtain the activity cost of each activity ($Cost_a$). $Cost_a$ is sum of cost due to AWT (C_{CAWT_a}) and the cost of executing activities (C_a). C_{CAWT_a} multiples AWT and the cost of AWT ($CAWT_a$). The cost of AWT is half the price of worker salary (C_{a_r}) [9]. The cost of executing activities contains the salary of the worker and the equipment cost

(C_{a_e}). The worker salary is calculated according to the activity processing time and the number of workers (n_{r_a}). Activity processing time is the subtraction of the end time activity (ETE_{a_i}) with the start time activity (STE_{a_i}). The activity cost of each activity is stored in a list of cost arrays named $totalCost$.

$$C_{CAWT_a} = AWT_a \times CAWT_a \tag{8}$$

$$C_a = \sum_{i=1}^{n} \left(\left((ETE_{a_i} - STE_{a_i}) \times C_{a_r} \times n_{r_a} \right) + (C_{a_e}) \right) \tag{9}$$

$$Cost_a = C_{CAWT_a} + C_a \tag{10}$$

Furthermore, this study runs the hybrid simulation with alternative numbers of workers to get AWT and activity cost for each number of workers and choosing the optimal workers using MCDM methods. The range of worker numbers is one until the number of workers producing an AWT value close to 0.

This study improved MCDM methods by applying MCDM methods in selected simulation activities. The aim of improved MCDM methods is to optimise the usage of MCDM methods. This study applies MCDM if the processing time of the activity ($processingTime_a$) is longer than that of previous activity ($processingTime_{a-1}$) because AWT occurs in this condition. Furthermore, there are additional rules for an activity that has a relationship with more than one previous activity. If the previous activities are in parallel relationship (AND relationship), then the maximum processing time is chosen because the activities in parallel relationship can move to the next activity if all activities are executed. On the other hand, the minimum processing time is chosen if previous activities are in choice (XOR or OR relationships). The improved MCDM methods are described in Algorithm 3.

The MCDM methods are MOORA and COPRAS, where AWT and activity cost are parameters. This study determined five types of weights of AWT and activity costs. The weights of AWT are 0.2, 0.3, 0.5, 0.7 and 0.8, while the activity cost weights are AWT weights in reverse order.

Algorithm 3. Optimising using MCDM-based simulation

Input: $totalAWT$ and $totalCost$

Output: $totalWorker$

for a = 0 to the last Activity **do**
  if $a \neq 0$ **and** $relationship(a-1, a) > 1$ **then**
    if $relationship(a-1, a) = parallel$ **then**
      $processingTime_{a-1}$ = max $\{processingTime_{a-1_0}, \dots, processingTime_{a-1_n})$
    else if $relationship(a-1, a) = choice$ **then**
      $processingTime_{a-1}$ = min $\{processingTime_{a-1_0}, \dots, processingTime_{a-1_n})$
    endif endif
  if $a \neq 0$ **or** $\frac{processingTime_{a-1}}{totalWorker_{a-1}} \leq processingTime_a$ **then**
    $totalWorker_a \leftarrow$ MCDM$(totalCost_a, totalAWT_a)$
  else then
    $totalWorker_a \leftarrow 1$
  end if end for
return $totalWorker$

4. RESULT

The proposed hybrid modelling was evaluated on the normal and overload conditions. The hybrid modelling using the MOORA method based on Algorithm 3 is called a hybrid modelling with improved MOORA, while that using the COPRAS method is a hybrid modelling with improved COPRAS. The simulation is built in Anylogic, and the MCDM methods are programmed using Python. This study implements the improved MCDM methods based on the proposed rules of Algorithm 3 and reduces the number of activities selected by the MCDM methods (from 37 activities to 27 activities). The improved MCDM methods save 27 % of the processing time of MCDM.

Table II shows the comparison of the actual model and hybrid modelling (simulations with improved MOORA or improved COPRAS) with equal weighting (0.5 weight of *AWT* and 0.5 weight of activity cost) under normal and overload conditions. According to Table II, the hybrid modelling decreases 38 % of the *AWT* and 22 % of the activity cost compared to the actual model under normal conditions. The hybrid modelling also decreased *AWT* and activity cost than the actual model under overload condition (73 % of *AWT* and 31 % of activity cost). Although MOORA and COPRAS reduce *AWT* and activity cost, MOORA performs better than COPRAS if the preferred parameter is activity cost, whereas COPRAS decreases more *AWT* than MOORA. In addition, the optimisation results recommend transferring some workers in the waste operation to the waste documentation operation without adding new workers.

This study also evaluates COPRAS and MOORA with unequal weighting under normal and overload conditions. The bold scores in Table III represent the best result based on the parameters that have higher weights. The evaluation shows that MOORA has better results when the activity cost has a higher weight than the *AWT*, and vice versa for COPRAS. In conclusion, MOORA is the efficient MCDM method when the preferred parameter is the activity cost, and COPRAS is chosen when the preferred parameter is *AWT*.

The evaluations verified that the novel hybrid modelling optimises waste management collaboration processes, as well as minimises *AWT* and activity cost. However, there are lacks in the novel hybrid modelling. First, the additional proposed rules of improved MCDM methods work well if the processing time from the first activity to the last activity is getting shorter. If the process condition is reversed, the additional rules did not have the maximum impact on the processing time of the MCDM. Second, the assigned workers in this case study have the same processing time to handle the same activity, so the processing time is fixed value. These shortcomings will become material for future development.

Table II: Comparison table between actual model and optimisation results with equal weighting.

Normal condition	**Actual model**	**Hybrid modelling with improved MOORA**	**Hybrid modelling with improved COPRAS**
AWT (hours)	64	39.4 (38.2 % ↓)	39.0 (38.8 % ↓)
Activity Cost (IDR MM)	115.5	88.7 (23.2 % ↓)	90.8 (21.4 % ↓)
Total number of workers in waste operation process	74	38 (48.6 % ↓)	38 (48.6 % ↓)
Total number of workers in waste documentation operation process	20	23 (15.0 % ↑)	24 (20.0 % ↑)
States of ABS	12	17 (41.7 % ↑)	17 (41.7 % ↑)
Overload condition	**Actual model**	**Hybrid modelling with improved MOORA**	**Hybrid modelling with improved COPRAS**
AWT (hours)	97,509	25,431.3 (73.9 % ↓)	25,468.6 (73.9 % ↓)
Activity Cost (IDR MM)	3,864.8	2,626.1 (32.0 % ↓)	2,655.1 (31.3 % ↓)
Total number of workers in waste operation process	74	63 (14.9 % ↓)	65 (12.2 % ↓)
Total number of workers in waste documentation operation process	20	28 (40.0 % ↑)	32 (60.0 % ↑)
States of ABS	12	24 (100 % ↑)	25 (108.3 % ↑)

Table III: Optimisation results with unequal weighting.

Normal condition				
***AWT* weight : Cost weight**	**Hybrid modelling with improved MOORA**		**Hybrid modelling with improved COPRAS**	
	AWT (hours)	**Cost** (IDR MM)	***AWT*** (hours)	**Cost** (IDR MM)
0.2 : 0.8	192	**66.6**	159	69.4
0.3 : 0.7	68	**80.1**	55	82.8
0.7 : 0.3	32	104.0	**22**	113.5
0.8 : 0.2	22	122.3	**20**	126.6
Overload condition				
0.2 : 0.8	32,717	**2,234.4**	31,903	2,267.4
0.3 : 0.7	30,316	**3,876.4**	29,667	3,938.5
0.7 : 0.3	20,136	4,255.0	**19,443**	4,824.6
0.8 : 0.2	16,737	5,495.7	**16,322**	5,867.8

5. CONCLUSION

This study proposes hybrid modelling to optimise waste management collaboration processes considering asynchronous waiting time (*AWT*) and activity cost. Hybrid modelling simulates collaboration processes by integrating discrete event simulation (DES) and agent-based simulation (ABS), while MCDM methods (MOORA and COPRAS) are applied to determine the optimal number of workers, as well as minimise asynchronous waiting time and activity cost. This study proposes improved MCDM methods considering activity relationships to streamline the usage of MCDM methods.

The evaluation showed that the improved MCDM methods can reduce 27 % of the MCDM processing time. The evaluation showed that hybrid modelling decreased 38 % of the *AWT* and 22 % of the activity cost compared to the actual model under normal conditions and decreased 73 % of the *AWT* and 31 % of the activity cost under overload conditions. The evaluation also verified that the proposed hybrid modelling is cost-effective and time-effective compared to the actual model. The result can provide a reference that the MOORA method works well if the focus is to minimise activity cost and the COPRAS method works well if the focus is to minimise asynchronous waiting time. The proposed hybrid modelling is verified to model and optimise waste management collaboration processes. In this research, the MCDM method is applied to another platform, so in future work, this research will embed the MCDM method into Anylogic. Furthermore, this research will refine the proposed hybrid modelling to address workers with different activity execution times.

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