A Smart Sustainable approach for waste management in post-natural disaster phase

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Abstract. As an archipelago country, Indonesia is lied on the Pacific ring of fire - the center of active volcano and earthquake, located in tsunami-prone regions and several tectonic plates and had intense tropical rain, that places Indonesia at regular risk of earthquake, volcano eruption, tsunami, flood, and other natural disasters. Instead of nature and severity destructions, these natural disasters create a large volume of debris and waste, about 5 to 10 times of the solid waste generated usually, that have negative impacts on environmental, social and public health if not managed carefully. This study proposes a smart, sustainable approach for waste management in post-natural disaster. Some natural disaster happened in Indonesia was collected from Indonesia's National Disaster Mitigation Agency to identify the global waste and debris potential from the disaster. Smart, sustainable municipal waste management framework based on four priority areas of governance, economy, social and environment, from the previous study, is adopted to develop a post-disaster smart, sustainable waste management framework and a pre-design system. The proposed framework is focused on the technical mechanism for collecting and converting generated waste and debris into valuable materials that are integrated into the waste management system.

Keywords: Indonesia, Disaster waste, Framework, Smart, Sustainable

1. Introduction
Indonesia is a marvelous archipelago country, lied between the Indian and Pacific oceans, rich with gorgeous mountains, beaches, tropical areas, green forest, and natural environment. On the other hand, Indonesia is also lied on the center of active volcano and earthquake, located in tsunami-prone regions and several tectonic plates and had intense tropical rain, which is placed Indonesia as the most vulnerable country prone magnifies natural disaster. Volcano eruption, tsunami, earthquake, floods, forest fires, and landslides ae frequently happen in Indonesia. Indonesia's National Disaster Mitigation Agency, stated that there were at least 2,342 natural disasters in 2016 and 2,213 natural disasters in 2017 [1] which jeopardized Indonesian people and environment. This natural disaster not only creates natural and severity destructions (i.e. death, injured, property damages, destroyed infrastructure, and building) but also generates unavoidable and tremendous waste and debris. Managing waste and debris in post-natural disaster becomes very critical as they can create negative impacts on environment, social and public health. Furthermore, the waste and debris generated from the catastrophe are possibly mixed and contaminated with hazardous and toxic materials, which are very dangerous for human health and environmental performance. It was estimated that tsunami in Aceh generated 780,000 tonnes of waste and debris, while a mountain of waste and debris created other health and
environmental disasters. It was found that managing this waste and debris was very challenging due to technical and infrastructure issues.

This research aims to develop a post-disaster smart sustainable waste management framework and its design system based on four priority areas of governance, economy, social and environment, modified from municipal waste management framework in the previous municipal waste management study. It is expected that the contingency program improves disaster treatment in sustainable ways. A comprehensive literature review provides trend of waste management pyramid, circular economy as the baseline of purposed framework, ICT and IoT for disaster waste management system and smart-sustainable waste management system. A technical mechanism for handling, collecting and converting generated waste and debris into valuable materials that are integrated into the disaster recovery system is also proposed in this study. ICT and IoT are used for Information Computer Technology and Internet of Things to improve the efficiency and effectiveness of waste management.

2. Literature Review

2.1. The trend of waste management hierarchy
Waste has negative significant impacts not only on environment but also human if it does not manage properly. The waste creates pollution, greenhouse gas (GHG) emission, dirty environment that can create serious economic, social and environmental issues. Therefore, proper waste management becomes essential need to minimize the waste negative impacts. Moving up the hierarchy of waste management (prevention, reuse, reduce, recycle, remanufacturing, energy recovery and disposal) [2] as presented in Figure 1 is urgently required to achieve more sustainable waste management.

![Figure 1. The trend of waste management pyramid](image)

In Figure 1 The landfill is expected to be the last option with small portion or even zero portion in the hierarchy, while reduction activity is expected to be the top priority in waste management system. Therefore, a new concept of circular economy is expected to turn up the current WMS pyramid into sustainable WMS pyramid, in which the landfill will have the minimum portion of waste after reduction, recycling or composting energy recovery options. This trend of waste management considers achieving zero waste through the implementation of appropriate strategies related to consumer consumption behavior to treatment technology.

2.2. Circular Economy as the baseline for future disaster waste management system
A circular economy is an innovative system that has objectives to close the waste loop and to design waste out of the system. The circular economy offers transformations of waste management linear model into a more economic, social and environmentally responsible waste management system [3]. Circular economy facilitates the reduction of material depletion, waste landfillsing, dangerous pollution and emission, environmental degradation, energy leakage and narrowing energy through long-life design, good maintenance, recondition, remanufacturing, recycling and remodification as presented in Figure 2.
The fundamental principal of the circular economy is cradle to cradle which is in contrast with the make-take-waste system. The circular economy is the future way to achieve sustainable economic, social and environmental through keeping the more material (i.e. biological and technical materials) in production and consumption circle. Two main opportunities for implementing circular economy in waste management are turning waste into resource and using waste as energy source. This circular concept can be an effective approach to sustain disaster waste management.

2.3. Smart and sustainable waste management system
The sustainability of waste management can be achieved if it is proactive (not reactive), has objectives to minimize waste through the entire life cycle of waste management (from collection to disposal), and need cooperation amongst stakeholders. Therefore, a fundamental concept of sustainable and smart waste management for municipal waste developed from previous research in Figure 3 can be considered to enrich the development the purpose post-disaster waste management system.

Figure 2. Circular Economy as the fundamental approach

Figure 3. The fundamental concept of sustainable and smart waste management
Figure 3 illustrates the use of ICT and IoT as the core of the waste management system through the integration of four elements (i.e. governance, economy, society, and environment) which play important roles in achieving a sustainable disaster waste management system.

3. Methods
In-depth literature review and direct communication with Government agencies including Indonesia Indonesia national disaster management agency (BNPB), environmental department, and Non-Government Organisation (NGO) were carried out to gain data and information related to the post-disaster waste management in Aceh, Lombok, Yogyakarta, and Palu. The data is then used to identify the existing situation of the post-disaster waste management in those cities including the amount of the waste and debris, the collection strategy applied, the vehicle used, the temporary storages chosen, the appropriate treatment technologies conducted and landfill sites provided. An in-depth analysis was conducted for the existing models and approaches for disaster waste management. The result was then used as the fundamental framework for developing smart, sustainable municipal waste management framework based on four priority areas of governance, economy, social and environment. To help to formulate the framework, this research adopted municipal waste management framework conducted in the previous research. The framework is focused on the technical mechanism for handling, collecting and converting waste and debris into valuable materials that are integrated into the disaster recovery system. This framework considers the integration of ICT and IoT to waste management to improve the efficiency and effectiveness of waste management.

4. Result and discussion

4.1. Indonesia post-disaster waste stream and management
Earthquake and Tsunami predominantly create devastating impacts on Indonesia compared to the other natural disaster flood which is the most frequently hit Indonesia. The worst natural disaster was the Indian tsunami which hit Aceh in 2004. The tsunami created huge disaster waste in this area. The disaster waste was estimated to reach 780,000 tonnes, mainly containing C & D waste, vegetation, and soil waste. The waste including mixed building, households, woods, and vehicle wastes, was removed from the disaster area and sent to a landfill site to clean the area for the reconstruction process. The waste handling tools and transportation uses dump trucks belong to the municipal and contractors [4]. The handling, treatment, reuse and recycling processes of waste management mechanisms were applied to demolition waste. About 12,000 wood furniture was made from the tsunami [5]. However, there is very minimum information about how waste is exactly collected, stored, transported, and treated. The other natural disaster happened in Indonesia is earthquake in Lombok. During this catastrophe disaster, there were about 13,000 damage buildings. The waste and debris were estimated consist of C & D waste, vegetation, and soil waste. The collection strategy applied, the collection used very limited excavators thus the waste cleanup was very slow. Lack of heavy equipment limited the waste cleanup process. The cleanup process was conducted by Indonesian military and private companies using total 48 excavators. The community involvement was very limited as they have no knowledge on how to manage the disaster waste [6]. The other earthquake in Yogyakarta in 2006, created about 350,000 damage buildings and houses and produced about 2.9 million tones of waste and debris [7]. The disaster tsunami and earthquake recently also hit Palu in 2018, devastated environment and building, brought abundant waste and sweep people to death. Lack of an effective mechanism to warn people when the disaster-hit Palu, has caused massive destruction. The disaster has left complex issues including the massive volume of disaster waste (e.g. mixed soil, building materials, debris, trees, boats, household waste, and hazardous waste) which is poorly managed. There were about 68.451 house building destroyed, that created tons of mixed waste [8]. The waste was collected in the temporary waste boxes before they sent to final disposal place. Provincial Government of Palu provided conventional trucks, excavators and bulldozers to transport the waste from temporary waste collection to final disposal place. However, limited number of people, machines, and vehicles
delayed the waste management process, thus the waste was mountain everywhere. Some of the organic waste was burned to reduce mounted waste in the disaster location. Not only humans who were negatively affected by the disaster, a lot of animals (i.e. cows and goats) were poorly neglected and eat the waste for their food.

4.2. Lessons learned on waste management

Well preparation for potential disasters and its impacts are urgently required to help community, city, and area to reduce the impacts created from disasters. Such planning for post-natural disaster waste and debris waste management systems will prevent the issues of unmanaged massive waste, speed recovery process and avoid high cost and dangerous risks for mistakenly handling the waste. Some experience of natural disaster waste management presents good practices in waste management plan [9]. Generating a long period waste management plan has become priority of California City to prepare disaster impacts potentials. The plan includes waste collection and handling strategy, temporary waste storage, waste treatment technology (recycling programs), disposal, hazardous waste categorization, and waste management dissemination. Therefore, some formal and informal agreements between communities and cities are also conducted to get quick access to urgent needs of personal and equipment. Implementation of an appropriate treatment technology such as recycling, reconditioning and remanufacturing program [10], [11] in a place is very important to quickly expand the existing waste management capacity when a disaster occurs. An updated solid waste management plan is also very essential as it will present the existing waste management capacity, location and types to supporting agencies (communities and contractors) thus will help in responding the appropriate action during the disaster. In addition, developing a special communication approach involving local communication media has also helped to direct the community to manage their disaster waste [9]. Preparing waste management staff involving local community people is a great source of labor to help government in managing disaster waste. Identifying waste management transportation, equipment, and supplies before the disaster has a great impact to reduce the lack of resources and to improve the waste transfers. Providing the information on the collection and storage locations are necessary to be available during the disaster to help in transforming the waste. Furthermore, segregating hazardous waste strategy is essential to be applied for controlling and avoiding hazardous contamination from waste stream [12].

4.3. Role of ICT and human in post-natural disaster waste management

To transform the conventional waste management system into a smart and sustainable waste management system in post disasters, three essential factors including the role of technology, information, and human are essentially involved. The technology used in the disaster area is varying depended on the disaster types (i.e. landslide, volcano eruption, floods, tsunami, and earthquake), topography position and location (i.e. urban, semi-urban, rural areas), country (i.e. developed, developing countries), etc. [13]. Appropriate technology (e.g. machinery, vehicles) is required for collecting variety of waste (i.e. debris, building waste, automobiles, furniture, and electronic products), transporting from disaster areas to disposal centers, and threatening the waste. The waste management system in post-disaster is challenging and complex as the waste is often mixed and spread. However, the current waste management technology offered automatic waste collection system which changes the way waste collection system work with automatic technology by using ICT such as sensors for sorting process, GPS for waste transportation process monitor, logistic digital system, waste mobile apps, automatic compactor trucks etc. [14] Sources of waste information during post-disaster are important to be communicated and integrated through waste collection process, transportation and treatment. However, the most waste information during post-disaster is still collected by different organization (e.g. government and non-government organization) which has a lack communication and integration. Thus, there is missing communication and data integration that should be shared among the waste management stakeholders. Some research discussed the importance of waste data collection (i.e. big data), including to identify some issues during the waste management
operations and to make appropriate decisions to provide best solutions to collect, transport and threat the waste [15].

4.4. A sustainable post-disaster waste management framework

Learn from a developed country (sophisticated technology), and adopt the local contents, a framework to achieve sustainable waste management in post-disaster is developed. The framework covers five important waste management stages as illustrated in Figure 4. First stage concerns the understanding and estimation of potential debris and waste together with its approximate amount and type of waste. The second stage focuses on determination of the collection strategy and centers. The third stage concerns the selection of effective transportation and storage. Fourth is determining the appropriate treatment. The fifth is determining the proper sites of landfills.

| Waste type | Composition                                      |
|------------|--------------------------------------------------|
| Organic    | Green waste, trees, stumps, brush, leaf, animal   |
| Vehicle    | Automobile steel components, tires, plastic accessories |
| Bulky      | Furniture (couches, table, etc.), oven, plumbing fixtures (toilets, sinks) |
| Building   | Timber, concrete, brick, asphalt, plastic board, asbestos, |
| Wood       | Wood particle, garden trees, |
| Electronic | Computer, refrigerators, dispensers, AC, |

Generally, the volume of disaster waste reaches 5 to 15 times the annual waste generated. One house can generate 30 – 113 tons of waste, while amount of waste and debris can reach 4-15 million tons. The assessment and estimation of the waste volume, waste type, degree of mixed waste are specific factors used in this system. The assessment result is also used to determine the type of vehicles specifically. The second layer in the framework is determining collection strategy and separation. There are on-site and off-site separation strategies that can be used in this system [16]. The selection of the effective strategy depended on some factors, including time limitation, availability of...
the vehicles and human resources, waste composition and volume, public health risk. Determining effective transportation and storage. Effective transportation is determined based on waste volume and type. There are at least three types of vehicles to be considered in this system, including low-medium and high capacity trucks. In this research, sustainable waste treatment technologies are technologies that are expected to provide best economic and social performance for disaster waste management and a minimum negative impact on the environment, during the entire process of the waste treatment. This sustainable waste treatment technology can be used to help identify the most appropriate treatment technology of waste/ debris created from the disaster that is locally suited for the context of the disaster waste/materials type. The following Table 2 presents the waste treatment technology options offered in this framework [2], [17], [18].

| Treatments             | Organic materials | Vehicles materials | Bulky materials | Building materials | Woods, materials | Electronic, materials |
|------------------------|-------------------|--------------------|----------------|--------------------|------------------|----------------------|
| Composting             | Suitable          | Unsuitable         | Unsuitable     | Suitable           | Suitable         | Unsuitable           |
| Anaerobic digest       | Suitable          | Unsuitable         | Unsuitable     | Suitable           | Suitable         | Unsuitable           |
| Gas recovery           | Suitable          | Unsuitable         | Unsuitable     | Suitable           | Unsuitable       | Unsuitable           |
| Incineration           | Pretreatment      | Pretreatment       | Suitable       | Pretreatment       | Pretreatment     | Pretreatment         |
| Gasification           | Pretreatment      | Pretreatment       | Unsuitable     | Unsuitable         | Pretreatment     | Pretreatment         |
| Reduce                 | Suitable          | Suitable          | Suitable       | Suitable           | Suitable         | Suitable           |
| Reuse                  | Unsuitable        | Suitable          | Unsuitable     | Suitable           | Unsuitable       | Suitable           |
| Reconditioning         | Unsuitable        | Suitable          | Pretreatment   | Unsuitable         | Unsuitable       | Suitable           |
| Recycling              | Unsuitable        | Suitable          | Suitable       | Suitable           | Suitable         | Suitable           |
| Remanufacturing        | Unsuitable        | Suitable          | Unsuitable     | Unsuitable         | Unsuitable       | Suitable           |
| Remodification         | Unsuitable        | Pretreatment       | Unsuitable     | Unsuitable         | Unsuitable       | Pretreatment         |
| Landfill               | Pretreatment      | Unsuitable         | Pretreatment   | Pretreatment       | Pretreatment     | Unsuitable           |

Table 2 Illustrates the potential appropriate treatment technologies for different waste materials. For example, composting is suitable for most organic material including food waste, small trees, leaves, market waste, and is suitable mostly for wood materials from garden trees [19]. Anaerobic digestion and gas recovery are appropriate for organic materials and wood materials. Waste produced from electronic and household appliance are mostly suitable for reconditioning, recycling, remanufacturing and remodification [20]. The table is used for determining the appropriate treatment technology in system.

4.5. Pre-design of a smart post-disaster waste management system
Waste of post-disaster is categorized as unpredictable waste, not based on historical data or demand analysis. Thus, post-disaster waste management system requires a new approach which is able to provide accurate and real-time data information, appropriate technology, facility, and human skills. The use of ICT (e.g. sensors) and IoT (e.g web) become key factors to integrate physical and cyber system sustainable waste management system through waste sorting, waste collection, waste transportation, and waste disposal. In order to create a smart disaster waste management system, accurate and reliable waste data identification, collection and analysis are required. A specific data collection system is developed to effectively manage the waste, as illustrated in Figure 5. The system is expected to be able to identify the type of waste, amount of waste, fraction of waste (i.e. grouping based on waste properties – paper, glass, fibers, automobile parts, furniture, etc.) and treatment of waste (i.e. recycling, waste to energy, remanufacturing, landfilling). The data collection system is expanded through the use of ICT and IoT, including the use of bins equipped by sensors, the GPS location of collected waste, and the type and contents of waste using automatic sorting machines. The integration among the technology, ICT, and IoT is designed to improve the global waste collection system.
Figure 5. Pre-design of smart post disaster waste management system

Figure 5 illustrates a system which is able to estimate the different types of wastes generated from the disaster, the types of debris, the waste volume, the locations where debris are located, and the appropriate treatment technology can be applied. Integrated system which involves the use of high-quality technology such as sensors, big data, and other ICT infrastructures is essential factors in this system. A detailed design of the system is discussed in the future study.

4.6. Lessons for consideration

The sustainable smart post-disaster waste management (SSDWM) could be considered as an important framework for an effective and efficient waste management practice post-disaster phase in Indonesia. The SSDWM offers number of benefits including reduction of waste, improvement of job creation, economic development, human quality life improvement, fast and effective decision making and better information on waste management performance which can be real-time, accurate and reliable. However, the implementation of SSDWM also face number of challenges including unpredicted waste created from natural disaster, mixed waste which is highly contaminated with dangerous materials (pesticide, fuel, etc), and different waste impacts created from different natural disaster, thus need different approaches. On the other hand, there are also some opportunities offered by the purpose waste management, for example massive amount of waste means money, massive amount of waste means great resources, advanced waste collection and segregate technologies which can reduce the cost and time usages, and appropriate waste treatment based on the waste characteristics. Accordingly, to successfully implement the SSDWM, some technical approaches need to be conducted, including intensive education, and campaign of waste management, effective waste collection, transportation, treatment and landfill processes, appropriate ICT and IoT infrastructure election, and community, private sector, industry, and government participation.

5. Conclusion

Generally, developing countries like Indonesia suffer the most from natural disasters, as it appears that natural catastrophes hit that region more often. The difficult situation in this country comes from the fact that Indonesia is not prepared to face such crises, including waste management for disaster. In reality, Indonesia still has a big problem with its regular waste management as waste management in this country has not been adequate to meet the daily waste collection and handling. The situation will be even more difficult, in the event of a catastrophe. As a result, the lack of preparation will lead to an increase in losses in lives and properties. An efficient way, strategies, and plans must be prepared earlier to limit the potential destruction of the disaster. This research presents a smart, sustainable waste management framework as potential future solution. A further study is ongoing conducted to assess and evaluate the sustainability of the purposed disaster waste management system.

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