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Logistical Simulation for On-site Concrete Waste Management in Decommissioning

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Large amounts of concrete waste are likely to arise from the decommissioning of a Kori-1 nuclear power plant. Several studies have been conducted on decommissioning concrete waste in recent decades, however, they have been limited to contaminated concrete issues or were small pilot-scale experiments. This study constructed two industrial-scale models of on-site concrete waste management for clean as well as contaminated concrete. To evaluate the performance of both the models, simulations were conducted using the Flexsim software. The concrete particle size distribution of Kori-1 and concrete processor properties based on widely used construction equipment were used as sources of input data for the simulations. It was observed that it may take over two years to complete the on-site concrete management processes owing to the performance of existing processors. In addition, it was demonstrated that it is essential to identify bottlenecks in the system and enhance the performance of the relevant processors to avoid delays of the decommissioning schedule. Our results suggest that this novel approach can contribute to developing schedules or expediting delayed activities in the Kori-1 decommissioning project.

Keywords: Kori-1, Nuclear power plant decommissioning, Concrete waste management, Logistics, Discrete event, Continuous simulation

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1. Introduction

The Kori unit 1 Nuclear Power Plant (NPP) ceased operations in 2017 after 40 years of operations. It is planned to be dismantled and decommissioned by 2032. Since large amounts of concrete waste are expected to arise from the Kori-1 NPP decommissioning project, the dismantled concrete waste has been of great concern and growing interest in recent years.

In order to reduce the amount of contaminated concrete waste, many studies have been conducted overseas in recent decades in relation to removal of radionuclides from the contaminated concrete. For example, there are some overseas practices such as the high-quality aggregate recovery technology of Nuclear Power Engineering Center (NUPEC) in Japan [1], the contaminated concrete separation process developed by Atomic Energy Commission (CEA) in France and Electrical Testing Materials Arnhem (KEMA) in Netherlands [2], and the BelgoProcess in Belgium.

In general, the concrete waste generated from the Kori-1 decommissioning can be categorized as concrete rubble from the bioshield, scabbled concrete and other clean concrete. The clean and uncontaminated concrete is estimated to account for most of the concrete waste - as much as 99.8%. It is likely that the concrete rubble from the bioshield and the scabbled concrete will be contaminated.

In the experiment of Min et al. (2009), it was demonstrated that most of the radioactive nuclides were concentrated in the cement paste of the porous material rather than the dense aggregate such as gravel and sand in the activated concrete [3]. They developed a model for removal of radionuclides from concrete waste using a heat treatment and mechanical grinding method [3].

In this study, two industrial scale models were established which mainly deal with the on-site concrete waste management activities. One of them was the contaminated concrete waste separation model which modified the model of the Min et al. experiment. The other was the clean concrete waste release model.

In order to evaluate the performance of both models, simulations were conducted using the Flexsim. And a mixed discrete-continuous simulation method - a hybrid simulation combining the discrete events and the continuous fluid processes - was employed for the simulations.

The results demonstrated the accuracy of simulations and identified bottlenecks in each model. Then, alternatives for the bottlenecks were evaluated for different conditions. It was demonstrated that the contaminated concrete can be reduced by about 75% and that the clean concrete waste release activity is likely to have a critical impact on the Kori-1 decommissioning schedule.

2. Literature review

2.1 Reference project

Kori Unit 1 was formally announced as the first NPP decommissioning project in Korea. This project was selected as a reference project in this study. Kori unit 1 with a capacity of 587 MWe commenced its construction in 1972 and began commercial operation in 1978. After 40 years of operations, it ceased operations in 2017 [4].

According to the latest Kori-1 project schedule, the dismantling of the concrete structures is supposed to be executed from 2026 to 2030 and immediately followed by a site restoration which is scheduled for 2 years and will end in 2032 [4]. Since there will be no separate time for the on-site management of the concrete waste generated from the dismantling of concrete structures, it might be necessary to promptly treat and remove the concrete waste on-site in parallel with the demolition in order to begin the site remediation in a timely manner.

2.2 Characteristics of concrete

Most concrete consists of water, cement, gravel, sand, air and other additives. Similarly, NPP concrete is

Table 1. Composition of concrete for NPP

Material	Density	Weight	Volume
		(%)	(%)
Water	1.00	7.20	16.47
Cement	3.15	14.40	10.46
Fly ash	2.27	3.60	3.63
Sand	2.59	33.14	29.27
Gravel	2.72	41.54	34.93
Super-plasticizer	1.15	0.12	0.24
Air	-	-	5.00
Total	-	100	100

Table 2. Estimate of Kori-1 concrete waste

Type		Weight	Volume
		(ton)	(m^3)
Contaminated	Bioshield [5]	63.92	27.79
	Scabbled [6]	309.28	134.47
Clean	Others [7]	175,367.50	76,246.74
Total	-	175,740.70	76,409.00

composed of the same materials as shown in Table 1. In the concrete, a cement paste - a sufficiently hydrated product - acts as an adhesive to firmly bond the aggregates [3]. When consolidated, it becomes porous material. Therefore, it contains capillary water present in the micro-pores and free water present in the large pores [3]. Later, the pore water in the paste migrates out and leaves voids in the concrete material. In general, the cement paste can be obtained by removing gravel and sand from concrete, whereas cement mortar can be acquired by removing only gravel from concrete.

2.3 Decommissioning concrete waste

Table 2 shows the estimate of the Kori-1 concrete waste by waste type. Volume was obtained by employing a density (2.3 ton/m^3) to the concrete weight. It was predicted that the concrete waste falls into three categories–concrete rubble from the bioshield, scabbled concrete and other clean concrete. The bioshield and scabbled concrete is assumed to be contaminated.

According to a recent study [5], the amount of bioshield concrete was estimated on the assumptions that the neutron flux and specific activity closely correlate with the structure locations and that the waste level will be classified as very low level waste. The quantity of the scabbled concrete was based on the related estimation data in Ref. [6]. In the case of the other clean concrete which is classified as non-contaminated conventional construction waste, the amount is expected to account for 99.8% of the total weight. It was obtained from Ref. [7], based on the construction amount of Kori-2 which was constructed with almost the same power generation capacity and in a similar period.

The contaminated concrete can be divided into the bioshield concrete and the scabbled concrete. For Kori-1, it is assumed that the bioshield concrete will account for most contaminated concrete rubble and debris unless there is contamination around the sump or pool area. The bioshield concrete is regarded as volumetric contaminated concrete which is subjected to removal by cutting or crushing. Its final state is expected to be in the forms of rubble or debris. On the other hand, the scrabbled concrete is removed by chipping and grinding the surface of concrete structures to a certain depth.

Clean concrete in cleared buildings – i.e. uncontaminated concrete - will account for almost all of the volume. It is anticipated that the clean concrete waste arising from the Kori-1 decommissioning can be treated as conventional construction waste without the self-disposal process by clearing the decontaminated building and the relevant controlled area at the same time. In general, the buildings and related controlled areas tend to be simultaneously cleared after radioactivity measurements prior to being dismantled [8]. Then, it is possible to manage the concrete as conventional waste, recycling resource or landfill material.

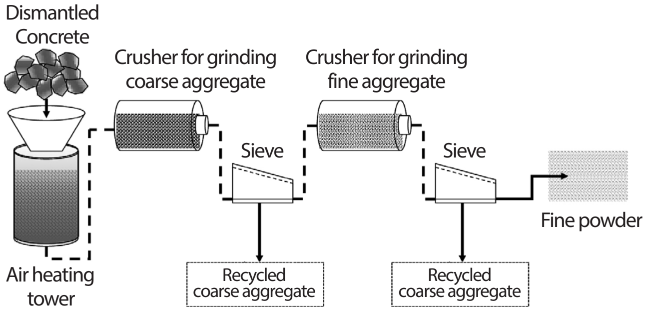

Fig. 1. High-quality aggregate recovery technology in NUPEC.

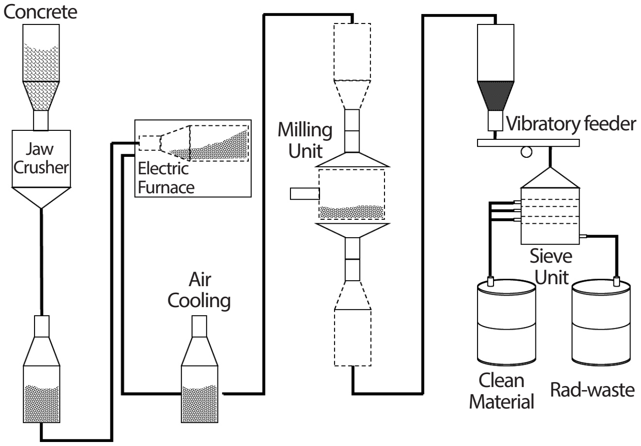

Fig. 2. KEMA concrete separation process diagram.

2.4 Radionuclides removal practices

In order to reduce the amount of contaminated concrete waste, many studies have been conducted overseas in recent years relating to removing radionuclides from the contaminated concrete. Since most radioactive contaminants are present in the cement paste, it is important to separate contaminated cement paste from aggregate such as gravel and sand [3]. In this case, the paste with a relatively weak abrasion resistance can be separated selectively by mechanical grinding or crushing after the adhesive performance of paste is removed by the heating [3].

As depicted in Fig. 1, NUPEC devised a high-quality aggregate recovery technology in preparation for non-radioactive concrete wastes, in order to recover coarse and fine aggregates from NPP concrete waste by mechanical grinding with a crusher and heat treatment [1].

A contaminated concrete separation process was developed jointly by CEA in France, KEMA in Netherlands and British Nuclear Fuels Limited (BNFL) in the UK using a pilot scale facility, in order to recycle radioactive concrete waste by high temperature heat treatment. As in Fig. 2, this system contained a set of processes in the order of crushing, heating, milling, and sieving to collect the particles larger than 1mm in diameter [2].

The BelgoProcess is a commercial-scale concrete crushing and sampling facility for the purpose of the minimum generation and the unlimited release of the concrete wastes. It has been employed at SCK-BR3 in Belgium [8].

2.5 Disposal of concrete waste

The contaminated concrete wastes must be recycled or landfilled through self-disposal, which can be entrusted to external vendors. On the other hand, the clean concrete arising from the buildings which are cleared or exempted from the controlled area can be taken out as conventional construction waste after radiation measurement.

In accordance with the Nuclear Safety and Security Commission (NSSC) Notice No. 2017-65 [9], the self-disposal of concrete wastes is defined as a behavior of landfill or recycling to manage the radioactive waste that can be treated as non-radioactive waste since it has been confirmed to contain the nuclear species concentration below the allowable limit of the self-disposal concentration. The self-disposal allowable concentration refers to the concentration at which the radioactive nuclide radioactivity concentration is proved to satisfy the allowable concentration or the self-disposal allowable dose [9]. In the case of self-disposal wastes, it may be temporarily stored in an on-site storage facility other than the controlled area where there is no possibility for contamination to spread [9].

In order to take the byproducts generated in the conservation area outside of the nuclear power plant boundary, it is necessary to measure the radioactivity and meet the off-site shipping criteria consistent with the internal procedures of the Kori-1 NPP. The conservation area refers to a place where special care is required for the conservation of nuclear facilities.

The majority of radioactivity detections are carried out by surface radiation dose rate measurement, the surface contamination level measurement and the radionuclide analysis. The direct measurement method - which is a method of measuring the contamination level by positioning the measuring equipment as close as possible to the target area or material surface to be measured - shall be mainly used for the surface radiation dose rate except for unavoidable cases [9]. If there are some nuclides present exceeding the concentration limit, theoretical methods can be used to assess the radioactivity concentrations for each radionuclide and demonstrate that it meets the self-disposal criteria [9].

2.6 Concept of simulation

Simulation can be used for the Kori-1 decommissioning as follows: i) forecasting waste flows ii) providing the best logistics scenario and optimal configuration iii) acquiring related information during all the steps of processes [10].

Simulation is a process of building and examining a virtual prototype of a real-world system under specific conditions [11]. The virtual environment provides the opportunity for carrying out a set of trials for various scenarios and obtaining the related information and the ideas for performance improvement with no risk of negative impact on the real-world system. In other words, it allows the evaluation of the specific system behaviors according to time, the comparison of alternative designs, “what-if” scenario analysis and a powerful problem-solving tool in a shorter time frame and at a less cost than the real-world system [10, 12].

Discrete event simulation is a transaction-based approach which is useful for the analyses of the cycle time, the inter-process correlation and the utilization state in a specific system [12]. In the relevant processors, state variables change at a discrete time interval during the specific ‘events’ which are typically demonstrated as a process cycle time, a scheduled activity and etc. in the system [13]. Thus, the discrete event simulation can be used for analyzing a batch manufacturing processes since the batch cycle time tends to act as the discrete intervals in the batch processing systems [12]. In other words, the batch is simply supposed to wait for a specific period of the simulation time as a delayed time before proceeding to the next step [12].

In continuous fluid simulation, the state variables of the associated processors vary in a continuous and smooth manner from one state to another [13]. In comparison with the discrete event simulation, this approach has a noticeable advantage that a calculation time is less sensitive to the size problem which results from the large amount of units and events [13]. Therefore, it is appropriate to represent fluid behaviors as a continuous flow. In some cases, not only liquid and gas but also small particles such as grains or sand can be regarded as a fluid. Furthermore, even if large flow items such as concrete rubble are processed at high speeds, they can be considered as fluid in the context of the continuous fluid concept [14].

A mixed discrete-continuous simulation is a hybrid simulation combining the discrete events and the continuous fluid processes. It has both discrete and continuous behaviors [13]. Hence, it is mainly used when continuous fluid and discrete events must be considered at the same time. For example, it can be used in a beverage manufacturing plant where the continuous fluid behavior of producing the contents and the discrete event of packaging the beverage must be demonstrated together [14].

3. Application of technology

3.1 Selection of technology

Min et al. (2009) demonstrated experimentally the removal of radionuclides from radio-activated concrete on

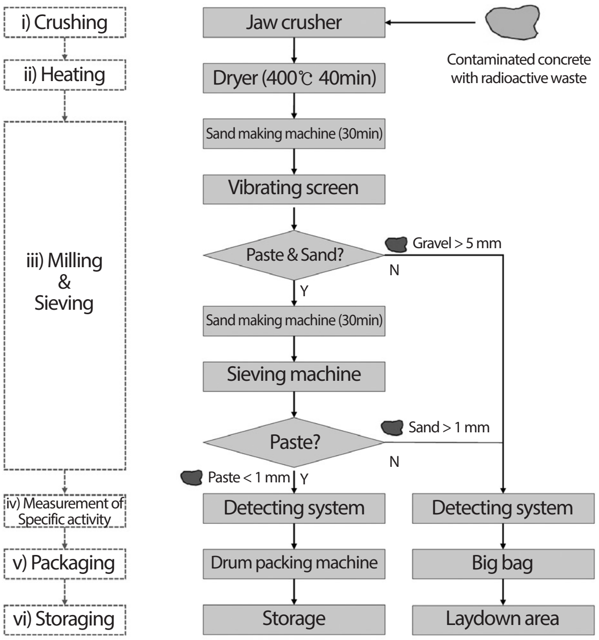

Fig. 3. Process diagram of the contaminated concrete separation model.

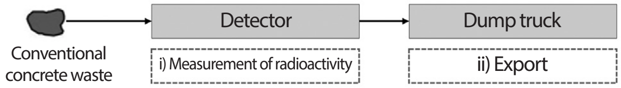

Fig. 4. Process diagram of the clean concrete release model.

the grounds that most of the radionuclides are concentrated in the porous cement paste rather than the dense aggregate such as gravel and sand in the radio-activated concrete [3].

In their experiments, the heating process noticeably affected the removal of radionuclides from the concrete waste by separating the paste from the contaminated concrete. After the concrete was heated at 400℃ for 40 minutes in a furnace and crushed for 30 minutes in a crusher, the coarse aggregate of 5 mm or more diameter gravel and the fine aggregate of 1 - 5 mm size sand were separated. Last, the separated particles were detected. As a result, it was demonstrated that no radioactivity was present in gravel and sand [3]. Furthermore, it was assumed that there is no gaseous waste generated from the experiment since all the radionuclides are incorporated in cement paste particle. In addition, liquid waste was not taken into account because all the processes were executed under dry conditions.

This study mainly dealt with a range of on-site concrete management activities based on the experimental model from Min et al. On the other hand, it expanded the previous pilot scale experiments of Min et al. to a real industrial-scale system in the on-site contaminated concrete separation model. In addition, packaging and storage steps were added in order to reflect the-site real workflow.

3.2 Contaminated concrete separation process

Fig. 3 shows the model of the contaminated concrete separation system which mainly deals with a range of the on-site activities from crushing to packaging.

In a jaw-crusher, the demolished concrete is crushed into concrete rubble of about 50 mm diameter. The concrete rubble is then transported to a heating dryer and heated for 40 minutes at about 400℃. The heated concrete is loaded in a sand making machine and crushed for 30 minutes. This process separates the gravel of 5 mm or more diameter from the heated concrete. Whereas, the separated mortar is delivered to the sand making machine and crushed for 30 minutes again for sieving, which separates the sand of 1-5 mm diameter from the mortar. Next, all the separated particles are supposed to pass through a radioactivity detection system which has enough sensitivity and accuracy to achieve the radionuclides separation goal.

Especially, it should be ensured that the separated paste which contain all the contaminants are detected separately away from the uncontaminated aggregate particles. In other words, separate detection systems should be allocated for the uncontaminated aggregate and the contaminated paste respectively, for the purpose of avoiding re-contamination from the unnecessary contact between the contaminated and the uncontaminated materials. Last, the contaminated cement paste particles of less than 1 mm size are collected in a 200 L drum for the temporary storage prior to permanent disposal while the aggregates over 1 mm size are collected in a big bag for self-disposal.

Table 3. Volume conversion factor for package

Type	Content	Conversion factor
Drum (200 L)	Paste - Bioshield	6.50
	Paste - Scabbled	5.50
Big bag (1×1×1 m)	Sand	1.15
	Gravel	1.15
Dump truck (13 ton)	Rubble	1.50

Table 4. Size of processors

Type	Vendor	Model	Size	Quantity	Area
			W×L×H (m)	(ea)	(m^2)
Jaw crusher	K&W	PE500×750	2.03×1.92×2.00	1	3.89
Dryer	Huahong	Φ800×8000	0.80×8.00×0.80	1	6.40
Sand making machine	Huahong	800×600	0.80×0.60×H	2	0.96
Vibrating screen	K&W	3YZS2460	3.28×7.16×1.78	1	23.48
Sieving machine	FILTRA	FTI-1500	1.16×1.16×0.92	1	1.34
Drum packing machine	-	-	5.90×2.35×2.36*	1	13.00
Total	-	-	-	-	50.03

* Standard size of export container is adapted for size-unknown component.

3.3 Clean concrete release process

The on-site clean concrete release model has a comparatively simple structure as shown in Fig. 4. The demolished concrete is directly delivered to a detector for the radioactivity measurement without any other process. Last, the detected concrete are loaded in a dump truck and shipped to the disposal site as conventional construction wastes.

3.4 Other considerations

In order to put the resulting products into an applicable package, the quantity must be changed from weight to volume with the volume conversion factors based on the particle type as shown in Table 3. Volume conversion factors of a 200 L drum are calculated based on the paste type in consideration of the correlation of drum number and weight in Ref. [6]. In cases of sand, gravel and concrete rubble, 'the loose particle conversion factors' were employed in accordance with the standard of construction estimates [15].

As can be seen in Table 4, an area of only 50 m^2 is required to install all the processors which are necessary for building the on-site contaminated concrete separation system. It is assumed that an additional area as large as 100 m^2 is needed for things such as clearance between processors, work space and maintenance space. The total required area for normal system operation is estimated to be only 150 m^2. In comparison to the Kori-1 site area of about 5,000 m^2, it is merely 3%. Unless unpredicted bottlenecks which need queue areas for waiting flow items occur during the system operation, this system deployment is predicted to be affordable for the on-site operation.

4. Simulation

In this study, simulations - from the perspective of project scheduling management - provided a powerful tool for i) identifying bottlenecks and delays ii) evaluating cycle time and the interactions between various steps of processes iii) providing the best path forward [12].

The simulation models of the Kori-1 project were established with the Flexsim software - version 19.0.2, which is widely used for simulation of logistics planning in various industries. Flexsim provides many helpful modules and easy-to-use graphical user interfaces [16] for both discrete and continuous simulation in an object-oriented 3D modeling environment [13]. Furthermore, it visually delivers the operating logic of the simulation model [17].

Specifically, Flexsim provides tools for establishing and simulating a virtual model. In order to predict potential changes impact on system performance, the model is run and the simulated behavior is observed as it evolves over time with input data and model attributes. Modeling objects in Flexsim are largely divided into discrete objects and fluid objects. The discrete object is used for the discrete system in which the state of the system is changed by discrete events such as the arrival or departure of a flow item [14]. On the other hand, the fluid object is appropriate for the system in which the state variables change continuously over time, such as injecting liquid into a large container [14]. In the meantime, the mixed discrete-continuous simulation model can be established by combining the discrete objects and the continuous objects. Regardless of object type, every object is assigned specific properties and logic such as process time or order for its own function. By changing one of these properties or logic for each simulation, the performance of the simulation model can be evaluated.

Table 5. Concrete particle size distribution of Kori-1

Type	Content	Weight
	(mm)	(ton)
Bioshield	Paste (< 1)	16.18
	Sand (1 < , < 5)	21.18
	Gravel (>5)	26.56
	Sub Total	63.92
Scabbled	Paste (< 1)	78.30
	Sand (1 < , < 5)	102.50
	Gravel (> 5)	128.48
	Sub Total	309.28
Exemption	Rubble	175,367.50
Total		175,740.70

4.1 Model type

The mixed discrete-continuous simulation of continuous fluid based type was adopted for the simulation of the on-site concrete waste management flow during the Kori-1 decommissioning project since the continuous fluid and the discrete events should be considered at the same time for the simulation models. Although it is favorable to apply the discrete simulation for the batch processing of the radioactive waste in the light of traceability, the continuous fluid simulation was mainly used except for the downstream processes such as packaging, storaging, or export since large flow items such as concrete rubbles tend to act as a fluid if processed at a high rate [14]. Especially, the continuous system played a main role in representing behaviors or phenomena of the concrete waste flow system in which change value or state continuously with time. During the simulations, the discrete event modules or functions were added to represent some transaction-based activities. Discrete event conditions such as delay time were allocated to every processor so that a continuous fluid simulation model may act as the discrete event simulation model.

But the continuous fluid based simulation in Flexsim

Table 6. Set values of the contaminated concrete separation system

Item	Input	Cycle time	Rate
	(per cycle)	(min)	
Source 1	25.00 ton	0.00	-
Jaw crusher	25.00 ton	30.00	50.00 ton/hr
Dryer	1.00 ton	40.00	1.50 ton/hr
Sand making machine 1,2	25.00 ton	30.00	50.00 ton/hr
Vibrating screen	25.00 ton	15.00	100.00 ton/hr
Sieving machine	2.20 ton	60.00	2.20 ton/hr
Detecting system 1,2	25.00 ton	180.00	-
Loader 1,2	1.00 m^3/bag	0.68	-
Drum packing machine	1.00 drum	12.00	5.00 ea / hr

has some limitations concerning statistical tools and the flow item information since it is incorporated as a third party module. As opposed to the discrete event based model, it is not able to collect statistics regarding content, stay-time, throughput and work in progress of the simulated system. Furthermore, it is hard to handle the last flow item due to the lack of information on flow item traceability.

4.2 Input data

As can be seen in Table 5, the Kori-1 waste concrete is divided into gravel, sand and paste based on the particle size. This table is used as a main source of input data for the simulation models. And the values in Table 5 were derived from Table 1 and Table 2.

4.3 Set values for processors

In Table 6, the task-specific values or properties of each processor were set up following the requirements of the on-site contaminated concrete separation system as below:

- The input amount of source 1, which generates concrete rubble of 500 mm or more diameter, shall be decided through several simulations at a level that allows the system to perform without the congestion of flow items.
- The concrete rubble shall be crushed by the jaw crusher into the proper size before put into a dryer.
- The dryer shall run for 40 minutes every cycle to heat the crushed concrete.
- The heated concrete shall be crushed for the separation of the gravel which has the size of more than 5 mm by the sand making machine 1.
- The vibrating screen shall separate gravel or mortar from the crushed concrete.
- The separated mortar shall be crushed for the separation of the sand of the size between 1 and 5 mm by the sand making machine 2.
- The sieving machine shall separate sand or paste from the mortar.
- The detection system 1, 2 should run for more than 10,000 seconds in consideration of a gamma-ray detection time.
- Loaders 1 and 2 shall be used to put the gravel and the sand respectively into 1 m^3-size multi-layered plastic bags.
- The drum packing machine shall be used for packing the separated paste into 200 L steel drums.

Table 7. Set values of the clean concrete release system

Item	Input	Cycle time
	(per cycle)	(min)
Source 2	100.00 ton	0.00
Detecting system 3	100.00 ton	180.00
Loader 3	8.47 m^3	17.91
Dump truck (13 ton)	8.47 m^3	3.60
Security guard station	1.00 truck	5.00

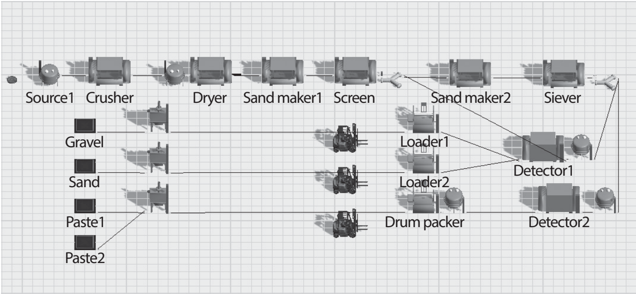

Fig. 5. Simulation model of the contaminated concrete separation.

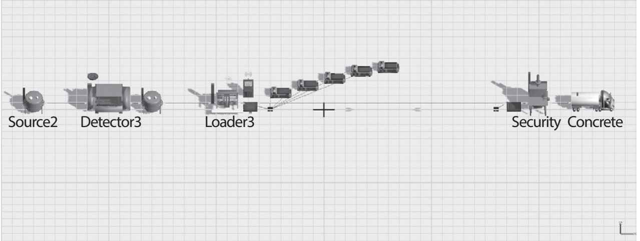

Fig. 6. Simulation model of the clean concrete release.

In order to meet these requirements, the process rate of each processor was determined based on widely used commercial machines in the construction industry. In the case of the dryer and the sieving machine, relatively low rate machines compared to the other processors were selected since there are not such large capacity machines which satisfy the above requirements in the market. Exceptionally, the rate of loader 1, 2 were calculated according to the standards for construction estimates [15].

As shown in Table 7, the set values of the clean concrete release system were chosen partially based on the contaminated concrete separation system. The input amount of source 2 was set at 100 ton per cycle, which allows for continuous system operation. The loader 3 cycle time per dump truck was calculated in line with the standards for construction estimates [15]. The input volume of a dump truck was calculated using the volume conversion factor of the concrete rubble in Table 3. Its cycle time was calculated in accordance with the standards for construction estimates [15]. At the security guard station, the access procedure was assumed to take at least 5 minutes per dump truck.

4.4 Assumptions

There were some assumptions and limitations for the simulation as follows:

- Every flow item such as sand particle flows immediately without any time delay from a processor to next one.
- The simulation runs continuously until the amount of flow items reaches the target discharge quantity.
- The system enters the utilized state almost simultaneously at the start of operation without any warm-up.
- There is no shutdown from equipment failure or maintenance activities.
- On the ground of above assumptions, the performance

Table 8. Simulation results of the contaminated concrete separation process

Type		Input		Output		Deviation	
		Weight (kg)	Pack (ea)	Weight (kg)	Pack (ea)	(kg)	(%)
Gravel		155,026	65.19	157,146	66	2,120	1.37%
Sand		123,678	54.61	124,795	55	1,117	0.90%
Paste							
	Scrabbled	78,311	105.98	78,334	106	23	0.03%
	Bioshield	16,185	25.88	16,250	26	65	0.40%
	Sub total	94,496	131.86	94,584	132	88	0.09%
Total		373,200	251.66	376,525	253	3,325	0.89%

improvement effect of the parallel deployment of two identical processors is same as that of doubling the rate of one processor.

- Last packs of each particle are discharged only in a full-filled state in order to meet the package requirement of the Wolsung disposal facility in Korea.

4.5 Simulation model

Fig. 5 displays the bird's-eye view of the on-site contaminated concrete separation model. This model mainly consists of the continuous fluid based processors except for the discrete event based section from the loaders (i.e. loader 1, 2 and drum packer) to just before sinks for gravel, sand and paste. At the end of flow stream, the resulting products were collected by particle size. The paste generated from the bioshield concrete is stored in the 'Paste1' sink while the scabbled concrete paste is stored in 'Paste2'.

Fig. 6 shows the bird's-eye view of the clean concrete separation model. This model also contains the discrete event based section as well as the continuous fluid based section. In this case, the discrete event based section is placed between the loader2 and the security station. At the end of flow stream, the resulting products are collected in the 'Concrete' sink.

Table 9. Reduction of the contaminated waste

Type	Amount	Ratio
	(kg)	(%)
Contaminated (paste)	94,584	25.13
Uncontaminated (aggregate)	281,941	74.87
Total	376,525	100.00

5. Results

5.1 Contaminated concrete separation process

In Table 8, the amount of resulting products were collected through simulation depending on particle size. The amount of the outputs was in good agreement with the input data. Although there were some deviations between the inputs and the outputs, they can be regarded as negligible due to the last pack assumption in 4.4. The pack quantities of the input and the output were calculated using the volume conversion factor in Table 3.

As can be seen in Table 9, it was proved that the clean materials can be retrieved up to nearly 75% while the contaminated materials were collected as few as 25% of the input amount. In addition, it indicates that the amount of the contaminated material was reduced by almost 75%.

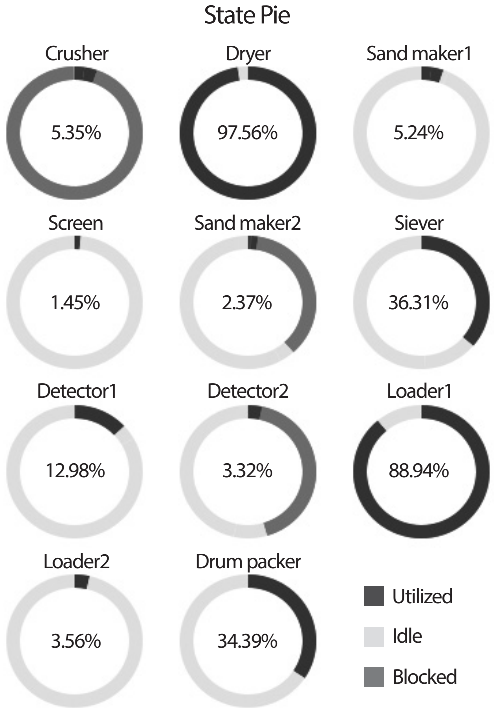

Fig. 7. Completion state before the dryer improvement.

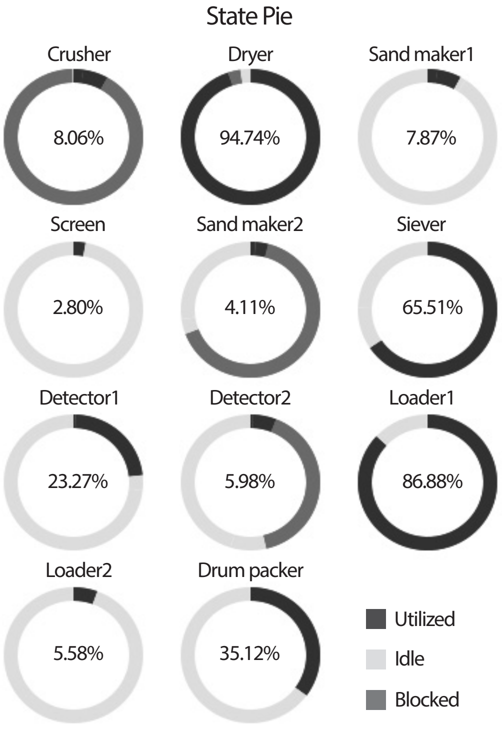

Fig. 8. Completion state after the dryer improvement.

Table 10. Dryer improvement effect on cycle time

Condition	Simulation	Calendar		
	(min)	(day)	(hr)	(min)
Dryer rate × 1	29,953	62	3	13
Dryer rate × 2	16,600	34	4	40

Table 11. Simulation results of the clean concrete release process

Type	Input	Output	Deviation	
	(kg)	(kg)	(kg)	(%)
Concrete	76,246,740	76,246,940	200	0.00%

The bottleneck and the saturation steps were identified in Fig. 7 and Fig. 8 which illustrates the states of the system processors on the moment of simulation completion. In the processor state legend of Fig. 7 and Fig. 8, ‘Utilized’ state means operation modes such as collecting, releasing, filling, mixing etc. On the other hand, ‘Idle’ state represents the empty, waiting and starved state. ‘Blocked’ state is regarded as a congested mode, which eventually leads to the stop of the whole system.

In Fig. 7, it is shown that the dryer was the first bottleneck since the dryer was quite close to its maximum and the crusher - the preceding processor - changed into an almost saturated or blocked state.

In Fig. 8, the process rate of the dryer was enhanced by 2 times with the aim of evaluating the proposed modification of the bottlenecked processor. As a result, the concentrated load on the dryer was distributed to other processors and the utilization rate of overall processors increased slightly except for the dryer and the loader 1.

Table 10 shows the comparison of the cycle times between the original dryer and the enhanced dryer. It took more than 2 months on the basis of 8 working hours per day to complete one cycle with the original dryer rate. When the rate of the dryer was increased by 2 times, it took only half the time to finish the same work. In terms of the

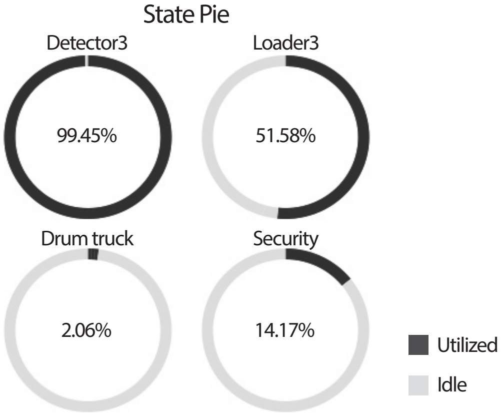

Fig. 9. Completion state before the detector improvement.

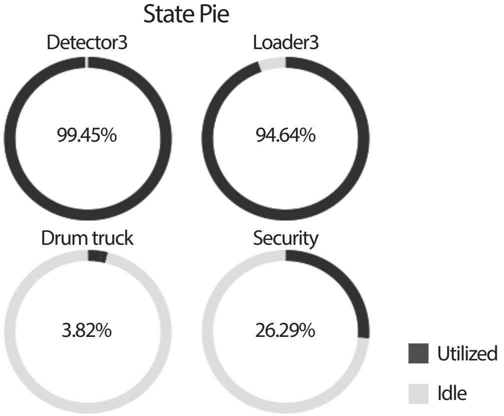

Fig. 10. Completion state after the detector improvement.

efficiency, the system was enhanced by about 45%. These results indicate that it is essential to identify bottlenecks and solve the relevant problems for saving time and improving efficiency of the system.

5.2 Clean concrete release process

Table 11 represents that the output amounts were almost consistent with the inputs since the deviation rate was close to 0%. This result is surmised to come from the fact that the concrete release process dealt with the input amount of 200 times more than the contaminated concrete separation process and had the deviation amount as little as nearly 6% of the contaminated concrete separation process.

Table 12. Detector improvement effect on cycle time

Condition	Simulation	Calendar		
	(min)	(day)	(hr)	(min)
Detector 3 rate × 1	317,560	661	4	40
Detector 3 rate × 2	171,229	356	5	49

In Fig. 9, the detector 3 was identified as the bottleneck in the clean concrete release system since the detector 3 got utilized almost 100%. In order to examine the effect of performance improvement on the bottleneck, the rate of the detector 3 increased by 2 times.

Although there was little difference in the utilization rate of detector 3, that of the loader 3 increased dramatically as shown in Fig. 10. It suggests that the bottleneck after the detector 3 is likely to occur at the loader 3 process. In other words, even if one bottleneck is identified and resolved, another bottleneck may be generated by another processor during the adjustment of the system performance to meet the target schedule.

Table 12 shows the cycle time comparison between the original detector and the enhanced one. It took nearly 2 years on the basis of 8 working hours per day to complete one cycle with the original detector rate. When the rate of detector 2 was increased by 2 times, it took only half the time to finish the same work. In respect with the efficiency, the system was improved by about 46%.

6. Conclusion

In order to evaluate the performance of both models, simulations were conducted using the Flexsim software. The mixed discrete-continuous simulation method was employed for these simulations. The estimated concrete particle size distribution of Kori-1 was used as the main source of input data for the simulations. In addition, the set values for processors were input based on widely used commercial machines in the construction industry. Each simulation run continuously until the amount of flow items reached the target discharge quantity.

The results verified that the simulations performed as intended since the outputs were in good agreement of input data. In addition, it was demonstrated that the contaminated concrete can be reduced by about 75%. In relation to the cycle times, it took more than 2 months to complete the contaminated concrete separation process on the basis of 8 working hours per day whereas it took approximately 2 years to finish the clean concrete release process. From the perspective of scheduling management, bottlenecks were identified and addressed partially by means of equipment performance improvement. For example, when the rates of bottlenecked processors were increased by 2 times, the whole system efficiency rose by about 45%. To sum up, it was observed that it may take more than 2 years to complete the on-site concrete management processes in consideration of the performances of existing processors. In addition, it was demonstrated it is essential to identify bottlenecks in the system and enhance these bottlenecked processors to avoid negative effects on the decommissioning schedule.

Notably, this is the first study to our knowledge to simulate and evaluate an industrial-scale model of on-site concrete waste management for a commercial NPP decommissioning project. Moreover, our results provide a powerful tool for the decommissioning scheduling management and suggest that this approach appears be effective in developing schedules or expediting delayed activities in the Kori-1 decommissioning project.

However, there seem to be some limitations. Although the required area for normal system operation was estimated so small as 3% of the Kori-1 site area, it is probable that an additional area is necessary to allow for unexpected occurrences of bottlenecks during simulations. Hence, additional study should be implemented in the near future regarding the required area by the system state.

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