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Original Article

Preliminary design of a production automation framework for a pyroprocessing facility

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ABSTRACT

Pyroprocessing technology has been regarded as a promising solution for recycling spent fuel in nuclear power plants. The Korea Atomic Energy Research Institute has been studying the current status of equipment and facilities for pyroprocessing and found that existing facilities are manually operated; therefore, their applications have been limited to laboratory scale because of low productivity and safety concerns. To extend the pyroprocessing technology to a commercial scale, the facility, including all the processing equipment and the material-handling devices, should be enhanced in view of automation. In an automated pyroprocessing facility, a supervised control system is needed to handle and manage material flow and associated operations. This article provides a preliminary design of the supervising system for pyroprocessing. In particular, a manufacturing execution system intended for an automated pyroprocessing facility, named Pyroprocessing Execution System, is proposed, by which the overall production process is automated via systematic collaboration with a planning system and a control system. Moreover, a simulation-based prototype system is presented to illustrate the operability of the proposed Pyroprocessing Execution System, and a simulation study to demonstrate the interoperability of the material-handling equipment with processing equipment is also provided.

1. Introduction

Various methods to recycle spent fuel in nuclear power plants have been extensively studied for a long time. Recently, pyroprocessing technology has been considered as a practical approach to sustainably recycle spent fuel. Pyroprocessing technology is known to be proliferation-resistant and to reduce the volume of high-level waste [1]. Accordingly, the Korea Atomic Energy Research Institute (KAERI) has been developing various types of equipment and devices to achieve a reliable and integrated pyroprocessing system.

From 1997 to 2006, a demonstration facility, named the Advanced spent fuel Conditioning Process Facility (ACPF), was developed by the KAERI, implementing major processes on a laboratory scale [2]. From 2007 to 2012, the KAERI developed an engineering-scale mock-up system for a cold test; this was the PyRoprocess Integrated inactive DEmonstration (PRIDE) facility. To verify the integrated pyroprocessing operability, the PRIDE facility implemented the whole pyroprocessing flow for surrogate material [3]. In fact, the PRIDE facility as an integrated pyroprocess facility is equipped with various types of remotely manipulated auxiliary devices for safe material-handling, such as a Bridge transported Dual arm Servo-Manipulator (BDSM) and a telemanipulator; these allow material flow throughout the whole pyroprocess to be synthetically generated [4]. Later, a desirable direction for a next facility and the basic design requirements for commercialization of a pyroprocessing facility have been discussed [5]. Table 1 provides major characteristics of these facilities. However, all the existing facilities (i.e., ACPF and PRIDE facility) are manually operated, either remotely or not. Manual operation is an obstacle that limits pyroprocessing experiments to laboratory scale. To extend the pyroprocess to commercial scale, the facility itself, including all the processing equipment and the material-handling devices, should be automated. Moreover, a supervised control system for automated production control should be employed to handle and manage the material flow and the operation of the automated equipment.

Conventional manufacturing facilities are equipped with a manufacturing execution system (MES) to enable automated

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Table 1
Characteristics of main pyroprocessing facilities in KAERI.

Facility	ACPF	PRIDE facility	Next facility
Mission	• Develop and verify main unit process	• Verify integrated pyroprocessing operability	• Specify design requirements for commercial use
Characteristics	• Laboratory scale	• Engineering scale	• Pilot facility with hot cells
Status	• In operation	• In operation	• Under preliminary design
Input material	• Simulated nuclear fuel	• Simulated nuclear fuel	• Spent nuclear fuel from nuclear power plants
Plant layout	• Single-station cells	• Production line (flow shop)	• Parallel production lines (job shop)
Material-handling method	• Manually handling	• Manually remote handling (BDSM/Telemanipulator)	• Automatically handling and *ad hoc* manually remote handling
Analysis issues	• Material behavior during individual unit processes • Overall material flow	• Operability of remote manipulators • Shop layout	• Logistics within facility • Plant layout

ACPF, Advanced spent fuel Conditioning Process Facility; BDSM, Bridge transported Dual arm Servo-Manipulator; KAERI, Korea Atomic Energy Research Institute; PRIDE, PyRoprocess Integrated inactive DEmonstration.

production beyond automatic control of individual pieces of equipment [6,7]. An MES is a computerized system that connects a business system [such as an enterprise resource planning (ERP) system] with shop-floor control equipment [e.g., various types of process control systems (PCS), including supervisory control and data acquisition (SCADA) systems, distributed control systems (DCS), and programmable logic controllers (PLC)] [8]. In practice, an MES provides linking of a production planning system with automated control systems, whereby an action plan translated into production activities is propagated into the whole shop floor and then changes in the shop floor resulting from its execution feed back into the planning system. As a planning-level system is usually not capable of controlling the equipment due to the real-time nature of shop floor, an MES is indispensable for accomplishing a series of automated production processes. MES implementations depend on the application environment. In addition, there is no literature available for an MES for a pyroprocessing facility or for other types of nuclear material engineering facility. Therefore, there is a research opportunity for a pyroprocessing facility to develop 1) an automation framework that defines interactive features of an MES with planning and control systems, 2) a control model that describes an operation flow through cooperative production activities of equipment, and 3) a decision-making model of an MES that purposes optimized production activities.

In this article, an MES intended for a pyroprocessing facility, named the Pyroprocessing Execution System (PES), is proposed, which functions as a production automation framework. PES collaborates with a planning system and a control system for the purpose of automatically performing overall production activities, from receiving the input material (i.e., spent nuclear fuel) to finishing the final product (i.e., recycled nuclear fuel). It is assumed that auxiliary devices for material-handling and processing equipment are automatically manipulated by automated control systems. In addition, a material-handling request–driven event model is employed as an operation flow model that defines a cooperation mechanism between the processing equipment and material-handling equipment. Moreover, a simulation-based prototype system is presented to illustrate operability of the proposed framework and the operation flow model. Then, a simulation study concerning interoperability of material-handling equipment with processing equipment is also described to provide insight into optimized production activities. The remainder of this article is organized as follows. Section 2 is devoted to describing the fundamentals and research trends of production automation in conventional manufacturing systems. Section 3 presents principal features of a pyroprocessing facility and then discusses design constraints and requirements for production automation. Section 4 proposes a functional architecture of a PES, together with description of the material-handling request–driven control model. Section 5 presents a simulation-based prototype system and a hypothetical simulation study. Finally, conclusions are provided in Section 6.

2. Production automation in conventional manufacturing systems

2.1. Production system and automation

A production system consists of various entities, such as people, equipment, and procedures, devoted to accomplishing given manufacturing operations, which can be categorized into manufacturing systems and manufacturing support systems [9]. A manufacturing system denotes a facility itself that contains processing equipment, material-handling equipment, inspection equipment, and control systems that handle manufacturing operations of all these types of equipment. Manufacturing support systems perform information-processing activities to manage overall production procedures and to work out problems with ordering materials, moving work through the manufacturing system, and ensuring quality. These activities include 1) business functions to deal with customer's requirements and cost accounting, 2) product design to comply with the requirements, 3) manufacturing planning to produce the product, and 4) manufacturing control to carry out the plan. To automate a production system, it is necessary to establish computerized operations of the manufacturing support systems and automated manipulation of facilities belonging to the production system.

As aforementioned, manufacturing support systems are in charge of widespread functionalities throughout from enterprise systems to control systems. In addition, the systems deal with highly complex information-processing activities. To deal with such high complexity, a functional hierarchy model has been generally employed as a reference architecture of manufacturing support systems, and a widely known one proposed by the International Society of Automation (ISA) is shown in Fig. 1 [10]. ISA has established an international standard for developing an automated interface between enterprise and control systems, entitled *ISA-95: Enterprise-Control System Integration* [11]. ISA-95 defines five levels of functional hierarchy as follows: 1) level 4 denotes the ERP layer, 2) level 3 denotes the MES layer, 3) level 2 and level 1 denote the PCS layer, and 4) level 0 represents the process itself. In the ERP layer, the financial and logistic activities including plant production scheduling and operation management are performed as business functions in the domain of the enterprise. The activities involved in the MES layer include production operations management, inventory operations management, maintenance operations management, and quality operations management, even if an MES itself is dedicated to manufacturing operations and control such as

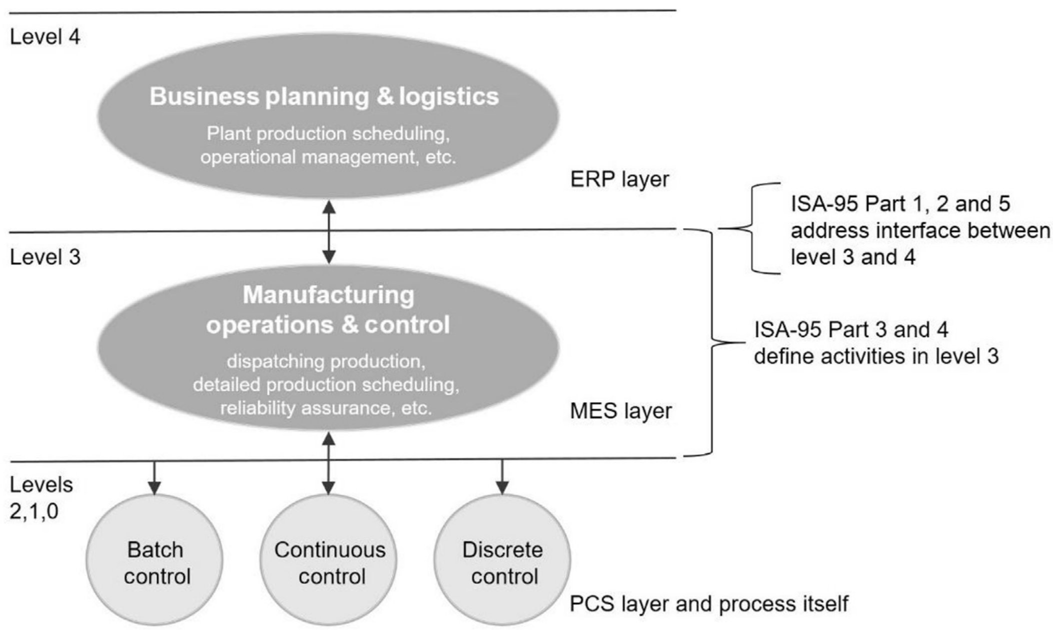

Fig. 1. ISA-95 functional hierarchy model [10].
ERP, enterprise resource planning; ISA, International Society of Automation; MES, manufacturing execution system; PCS, process control systems.

dispatching production, detailed production scheduling, and reliability assurance. The PCS layer addresses direct control activities of the physical equipment belonging to the shop floor, concerning execution of the actual production operations. In fact, an MES links enterprise systems (i.e., ERP system) with the control system (i.e., PCS) as an intermediary. Detailed functions and activities in the entire MES layer are described by the third part of the ISA-95 standard, entitled activity models of manufacturing operations management [12].

2.2. Manufacturing execution system

An MES in a broad sense performs highly comprehensive functions including production planning, production execution, operation management, and production management [8]. The MES may even, in the position of a production planning system, substitute for partial functionalities of an ERP system, a material requirement planning system, and a manufacturing resource planning system. However, in principle, an MES is a production management tool that integrates production planning with control and automation systems [13]. From the viewpoint of production planning and control, a production system shapes a three-tier hierarchy comprising a planning layer, execution layer, and control layer, as shown in Fig. 2. In practice, an MES is a control execution system to release production orders to a manufacturing system, to control the progress of the orders, and to acquire real-time information on the status of the orders [9]. The MES performs these tasks according to planned orders from a production planning system and reports order status to the planning system. The MES translates the orders into a detailed schedule to be executed at the control layer and monitors shop-floor states.

MESs are implemented in different forms depending on the application environment, especially the characteristics of the target facility. For instance, a flat panel display fab is a large-scale manufacturing facility consisting of innumerable pieces of expensive equipment; it adopts full capacity production requiring extensive utilization of equipment and just-in-time production involving minimum work-in-process (WIP). Therefore, sophisticated decision problems for job scheduling and dispatching should be solved in a real-time manner, considering a highly dynamic shop-floor environment [6]. In addition, the MES should be capable of responding to dynamic changes of shop floor. Fig. 3 shows a simple view of an MES architecture that has been applied to a major flat panel display manufacturing company in Korea [7]. As the core of the MES, a tracking system observes and updates WIP status in real time while managing all manufacturing resources, and it generates a sequence of work orders for a given planned order. Moreover, a job-dispatching command is issued in responsive collaboration with a real-time scheduler and a real-time dispatcher, based on the current WIP status.

Recent market dynamics have brought about the need for a responsive and agile MES [14]. The gap between a plan and actual shop-floor status has been widened by a highly dynamic and uncertain production environment. In consequence, a new paradigm of execution control has been introduced, called decentralized MES, which addresses robustness against disruptive events rather than optimality. In a decentralized MES, execution control functions are carried out via collaborations among several decentralized execution units. Its well-known instances are PROSA [15] and ADACOR [16], which are based on the holonic manufacturing concept. Recently, a relation-driven fractal organization [14], an autonomic MES [13], and a virtualization-aware MES [17] have also been proposed.

3. Pyroprocessing facility

3.1. Principal features

Pyroprocessing is an electrochemical process that uses a high-temperature molten salt bath to separate transuranic elements from nuclear fuel after which, that fuel is used by nuclear power plants [18]. Pyroprocessing consists of several unit processes: 1) electrolytic reduction from spent oxide fuel, 2) electrorefining, and 3) electrowinning; all these unit processes should be performed in a hot cell filled with argon gas. A pyroprocessing facility as a manufacturing system links the hot cell with a spent fuel unloading cell, a storage pool, a head-end cell for voloxidation, maintenance cells, and waste conditioning cells [5]. The toxic environment of such a facility makes a radical difference between

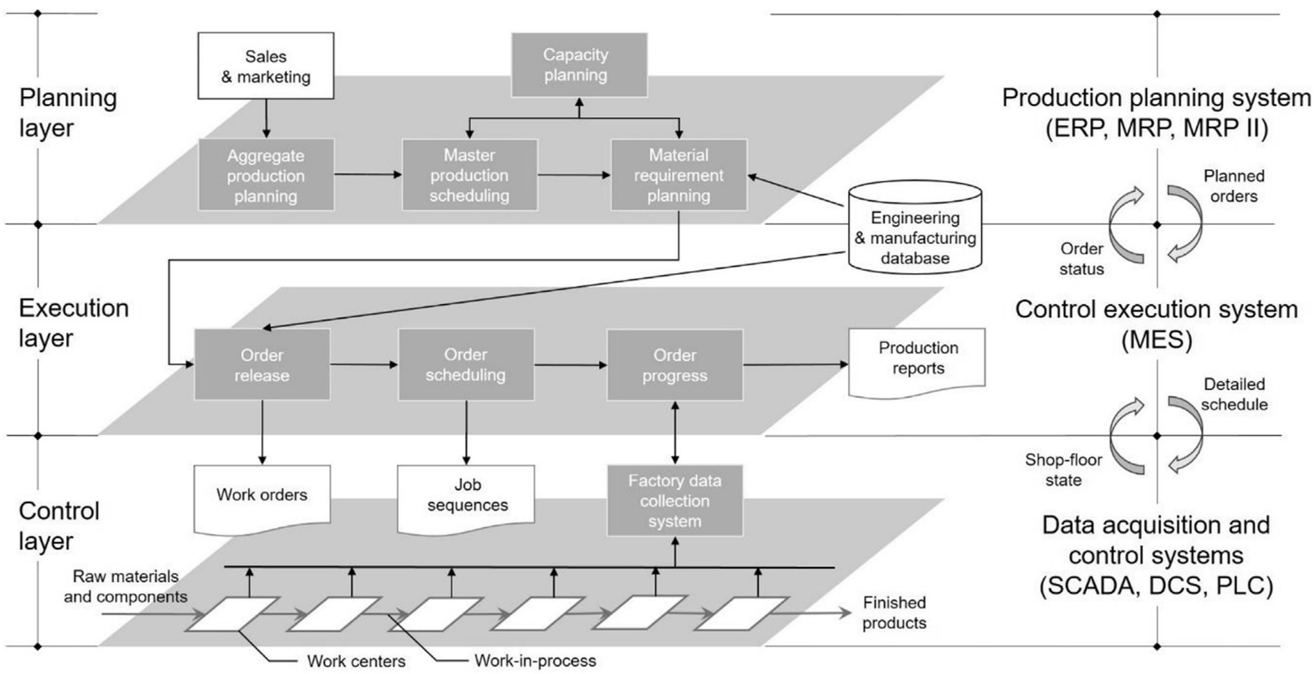

Fig. 2. Three-tier functional hierarchy for production planning and control.
DCS, distributed control systems; ERP, enterprise resource planning; MES, manufacturing execution system; MRP, material requirement planning; MRP II, manufacturing resource planning; PLC, programmable logic controllers; SCADA, supervisory control and data acquisition.

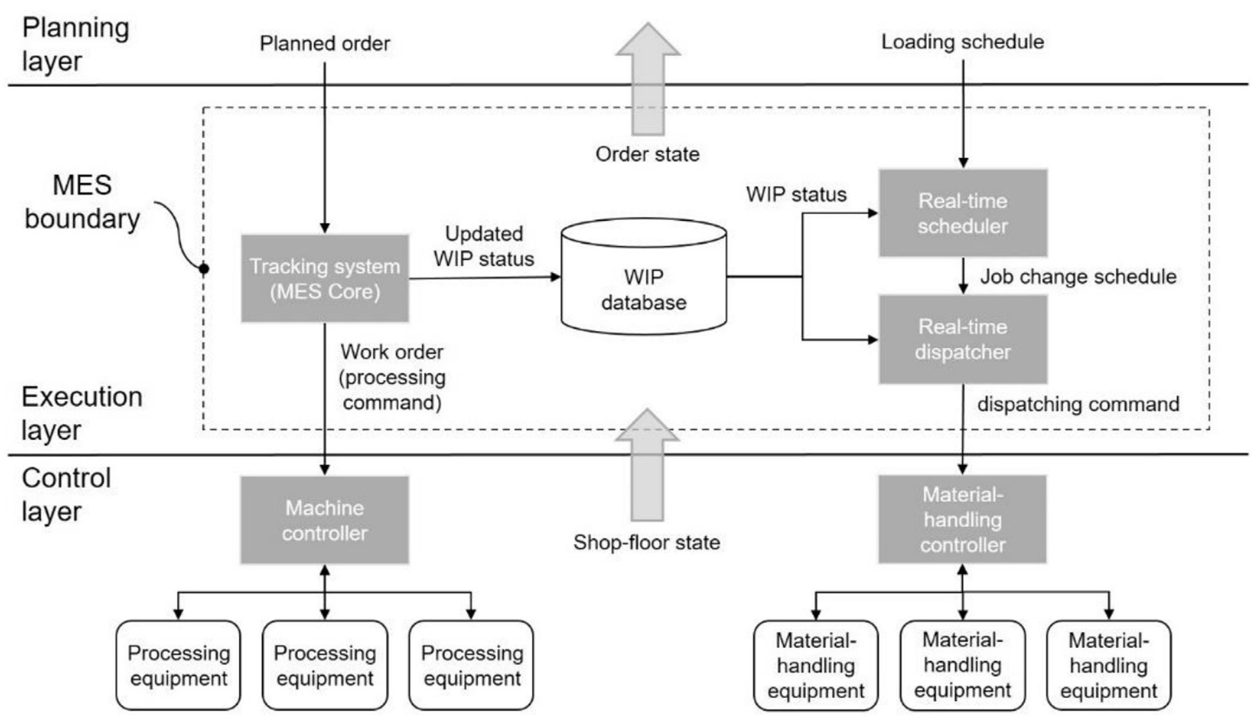

Fig. 3. MES architecture of a flat panel display fab [7].
MES, manufacturing execution system; WIP, work-in-process.

a pyroprocessing facility and conventional manufacturing systems. Moreover, human operators are definitely prohibited from directly accessing the in-cell; therefore, every piece of equipment (either processing or material-handling) belonging to the facility should be operated and maintained in a fully remote manner. In addition, totally safe and reliable material handling should be ensured because of the radioactive nature of input materials, and a complete overhaul of the facility is impossible once an operation is launched.

Furthermore, a pyroprocessing facility in the phase of commercial use shows several characteristic features from the viewpoint of conventional shop-floor logistics, as follows.

- *Static production plan*. A pyroprocessing facility is a production system dedicated to only a single product (i.e., recycled nuclear fuel) under a static production plan. It is intended to meet relatively stable public needs rather than fluctuating market needs. A conventional manufacturing system usually produces a multivariety of products to meet customers' diversified dynamic needs, and therefore, it is confronted with a complicated production planning problem for machine flexibility and routing flexibility. On the other hand, production planning in the pyroprocessing facility is rather straightforward, concerning a target throughput of its only final product.
- *Discrete process flow*. A pyroprocessing facility involves a discrete process flow, in which several unit processes are individually performed. A usual chemical engineering process dedicated to a single product adopts a continuous process to provide continuous chemical reactions and to reduce loss of operating time. On the other hand, even though pyroprocessing is a series of electrochemical processes for a single type of product and the execution order of unit processes cannot be changed, it is equipped with the processing equipment dedicated to respective unit processes and material-handling equipment connecting the processing equipment.
- *Job shop*. A pyroprocessing facility is a job shop, in which a job is not necessarily constrained to a single piece of processing equipment. In practice, there are multiple pieces of processing equipment dedicated to a unit process, and the same types of equipment are located in common areas, and individual WIPs move through the areas sequentially. Therefore, routing flexibility can be ensured, but equipment selection problem must be resolved.
- *Container-based material flow*. A pyroprocessing facility adopts various types of containers that are specially designed for nuclear material. Each container holds homogeneous material that achieves the same progress as that of the overall recycling process; this material is transferred from the processing equipment to the next step processing equipment. Each type of container has its own carrying capacity, and processing capacity depends on the carrying capacity of a container that holds input material for the process.

3.2. *Design requirements for execution control*

A pyroprocessing facility shows partially common features with other conventional manufacturing systems. For example, a flat panel display fab is also a job shop, and it shows discrete process flow and adopts container-based material flow. A container (which is called a cassette) holds a number of large-sized glasses and should be automatically handled because of its physical weight and size, its required throughput beyond the limits of manual handling, and other quality and productivity issues. However, because the flat panel display fab produces many types of products, the production planning problem itself is more complicated. In addition, real-time responsiveness to unexpected events is of importance to optimal execution control toward higher throughput and utilization. Therefore, the execution control system (i.e., MES) should be equipped with sophisticated scheduling and dispatching systems. On the other hand, in a pyroprocessing facility, robustness against exception and fault-tolerant execution control are recognized as more important because of the system's limited responsiveness.

The execution control system of a pyroprocessing facility is required to comply with several design requirements, as shown in Table 2. In a pyroprocessing facility, interaction of the execution control system with the planning layer is relatively straightforward due to the simplicity of production planning. However, it is highly coupled with the control layer to ensure robust execution control against unexpected events. In addition, it should be equipped with a maintenance system that is capable of maintaining the equipment in remote mode. Furthermore, the execution control system is required to adopt a discrete event–driven control model that fits the discrete process flow of a pyroprocessing facility. Especially, a material-handling request (e.g., load request and unload request)–driven event model conforms to the features of the job shop and container-based material flow. On the other hand, a flat panel display fab employs a process-tracking model for execution control; this model is suitable to represent complicated process transitions of a large-scale manufacturing system such as a flat panel display fab. Moreover, the pyroprocessing facility needs to adopt dispatching-oriented execution as opposed to closed-loop control throughout scheduling, dispatching, and execution, which is needed for more sophisticated scheduling, because the pyroprocessing scheduling problem is rather straightforward.

4. Pyroprocessing execution system

4.1. *Functional architecture*

PES is a dispatching-oriented execution control system intended for a pyroprocessing facility, in which a material-handling request–driven event model is applied for execution control. PES takes controls of batch processing by the unit of a set of material-handling lots, each of which is contained by a unit container. Fig. 4 shows the functional architecture of the PES.

- Pyro-DSP. Pyro-DSP is a dispatching system that generates a dispatching command (DspCmd) in response to a material-handling request (MHReq), considering the current shop-floor status with respect to equipment and WIP. A dispatching command represents a decision on the next piece of processing equipment for WIP or the next WIP allocated to the processing equipment.
- Pyro-MCS. Pyro-MCS is a material control system that makes a decision on the optimal transfer route for WIP and generates a material-handling command (MHCmd) for the material-handling equipment. The transfer route denotes a series of stopovers of WIP for changing material-handling equipment on the way to the final destination, specified by a dispatching command. The route is dynamically revised to balance workload of material-handling equipment.
- PlanMgr. PlanMgr manages supplies of raw materials under planned orders from a planning system. It creates a material-handling lot and requests material handling of the lot from Pyro-DSP. It is assumed that the raw material is automatically put in a container by an auxiliary handling device.
- WIPMgr. WIPMgr is a tracking system that observes every WIP located in a shop floor and updates WIP status according to progress of the WIP. For example, WIPMgr changes the current unit process of WIP to its next unit process after completion of the current unit process is notified by a process end event.
- EQPMgr. EQPMgr monitors the current status of processing equipment belonging to a facility and updates the equipment database that represents availability of the equipment. In addition, if a failure of equipment is detected, it changes the state of the equipment to DOWN and requests overhaul from an external maintenance system that is manually operated in remote mode.
- pEC. pEC denotes a processing equipment controller. It is a SCADA system that operates under a processing command over communication interfaces with processing equipment. It is assumed that the processing command is automatically issued

Table 2
Comparison of execution control between a flat panel display fab and a pyroprocessing facility.

Criterion	Flat panel display fab	Pyroprocessing facility
Design objective	• Real-time responsiveness to unexpected events	• Robustness against exception
Production environment	• Multiple product production • Dynamic production plan due to fluctuated market demand	• Single product production • Static production plan
Operation policy	• Optimal execution control for high throughput and high utilization	• Fault-tolerant execution control
Automation framework	• Complete integration of execution layer with planning system and control system • Fully automated processing and material handling	• Highly coupled execution layer with control layer but simple interaction with planning layer • Fully automated manipulation but manual maintenance in remote mode
Execution control model	• Discrete event–driven control model • Process tracking model with automated material-handling system • Closed-loop throughout scheduling, dispatching, and execution	• Discrete event–driven control model • Material-handling request–driven discrete event flow • Dispatching-oriented execution control

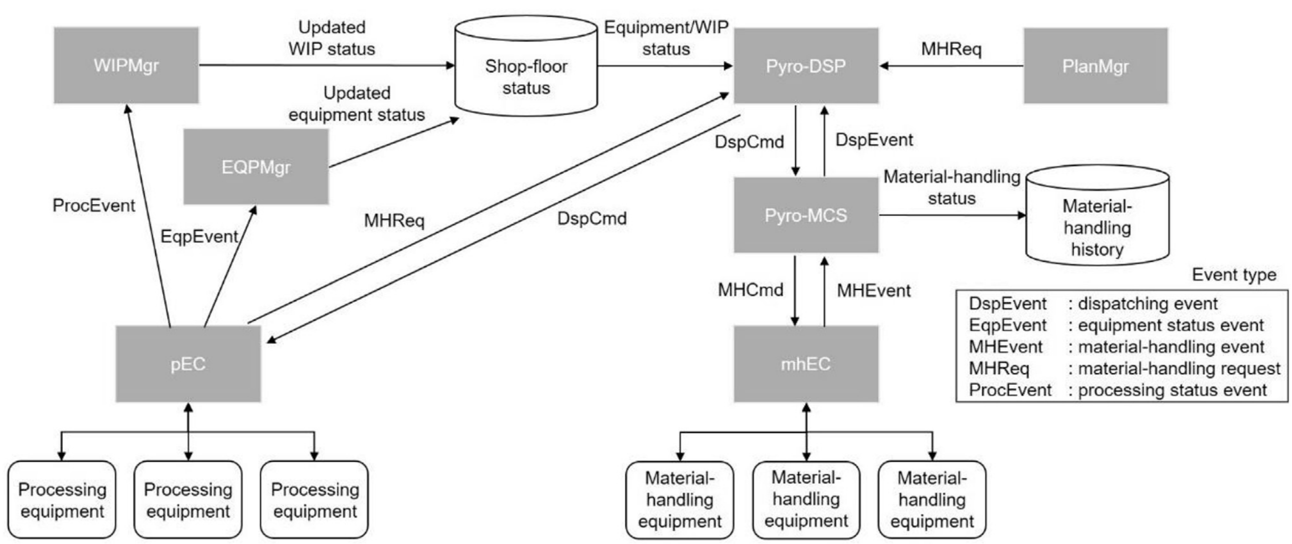

Fig. 4. Functional architecture of Pyroprocessing Execution System (PES).
DspCmd, dispatching command; MHCmd, material-handling command; pEC, processing equipment controller; WIP, work-in-progress.

by a loading event of WIP into an input port of processing equipment.

- mhEC. mhEC denotes a material-handling equipment controller. It is another SCADA system that operates under a material-handling command from Pyro-MCS, and it is equipped with a communication interface with its associated material-handling equipment.

Every piece of equipment (either processing or material-handling) is automatically manipulated by control commands of pEC or mhEC. PES does not explicitly provide sophisticated scheduling functions because process flow of the facility is straightforward. PES generates a sequence of work orders (i.e., processing and material-handling commands) based on dispatching rules.

4.2. Material-handling request–driven execution control

Execution control of PES follows a material-handling request–driven event flow. Material-handling requests are categorized into 1) load requests to processing equipment and 2) unload requests from processing equipment. A load request event (*LdReq*) triggers a pull flow of WIP toward the requesting equipment, which is involved in a decision problem of finding the next WIP among WIPs located on the shop floor. On the other hand, an unload request event (*UldReq*) creates a push flow of WIP from the requesting equipment, which requires a decision on the next destination (either another piece of processing equipment or temporary storage) of WIP completed by the equipment. Fig. 5 shows an execution control flow driven by an unload request. After pEC detects a process end event (*ProcEnd*) from the processing equipment, it triggers an unload request event and makes Pyro-DSP generate a dispatching command. Consecutively, Pyro-MCS generates a material-handling command, and mhEC commands a series of unit material-handling activities. Then, material-handling equipment unloads WIP from the source equipment, moves to the destination equipment, and loads the WIP to the equipment. Tables 3 and 4 provide main events involved in the execution control flow and specifications of exchanged messages in response to an event, respectively. Fig. 6 shows a material-handling history of a sample lot (LotID: LOT_0001), which is updated by Pyro-MCS in response to a material-handling event (MHEvent) from the mhEC.

5. Prototype system

5.1. System configuration

To illustrate the operability of the proposed PES, a prototype system was developed in the form of a virtual manufacturing system that adopts a simulation model of a pyroprocessing facility. Because a fully completed pyroprocessing facility is still under development, it is impossible to connect PES with a real shop floor. Therefore, it is required to make a substitute mechanism for real interactions

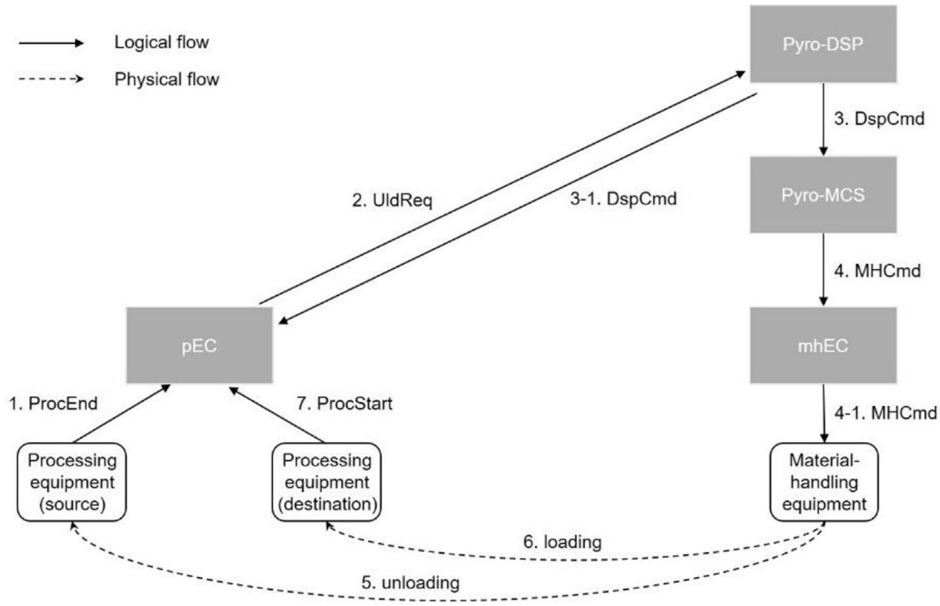

Fig. 5. Unload request–driven execution control flow.
DspCmd, dispatching command; MHCmd, material-handling command; pEC, processing equipment controller; ProcEnd, process end; ProcStart, process start; UldReq, unload request.

Table 3
Events list for material-handling request–driven execution control of PES.

Type	Event	Description (full name)
MHReq	*LdReq*	Request WIP load to equipment (load request)
	UldReq	Request WIP unload from equipment (unload request)
DspEvent	*DspCmd*	Receive a dispatching command from Pyro-DSP (dispatching command)
	DspStart	Start execution of a dispatching command (dispatching start)
	DspEnd	End execution of a dispatching command (dispatching end)
MHEvent	*MHCmd*	Receive a material-handling command from Pyro-MCS (material-handling command)
	MHReady	Ready for a transfer (material-handling ready)
	MHStart	Unload WIP from source equipment and start a transfer (material-handling start)
	MHEnd	Load WIP to target equipment and end a transfer (material-handling end)
ProcEvent	*ProcReady*	Receive a processing command (process ready)
	ProcStart	Start execution of a processing command (process start)
	ProcEnd	End execution of a processing command (process end)
EqpEvent	*EqpDown*	Change into a DOWN state in which the equipment is unavailable (equipment down)
	EqpRcvr	Change into an UP state in which the equipment is available (equipment recovery)

PES, Pyroprocessing Execution System; WIP, work-in-progress.

between PES and equipment. In this study, a dynamic simulation model was built for a facility to represent the behavior of equipment belonging to a pyroprocessing facility and its interactions with PES. A material-handling submodel within the facility simulation model is separated from a processing submodel to represent the independent behavior of both processing equipment and material-handling equipment and their series of interactions in substance.

Fig. 7 shows the configuration of the proposed prototype system. The prototype consists of two independent applications with an individual communication interface: an execution controller and a facility simulator. The execution controller includes main execution modules of PES (e.g., Pyro-DPS and Pyro-MCS). On the other hand, the facility simulator mimics behaviors of both the processing equipment and the material-handling equipment and also functions as an equipment controller (i.e., pEC or mhEC) in collaboration with the execution controller. pEC and mhEC within the simulator respond to a command from the execution controller according to the corresponding simulation result. Such a modular design helps the execution controller to secure reusability for various types of control systems.

To develop a prototype system, static information (e.g., process information and capability of equipment) and dynamic information is needed. Once the prototype system is constructed based on the static information, it produces a dynamic output such as productivity report, WIP profile, and production schedule according to predefined dispatching rules, for a given input data (i.e., a production plan, the present condition of WIP and equipment).

5.2. Implementation

The proposed execution controller and the facility simulator were developed using Java and AnyLogic, respectively. AnyLogic is a simulation modeling tool that supports a discrete event simulation method; it also provides interfaces to Java code [19]. More specifically, simulation models of the facility (containing the processing and material-handling submodels) are AnyLogic models embedded in a Java runtime application that implements both pEC objects and mhEC objects. Fig. 8 shows the simulation model (in terms of statechart diagram) along with a graphical view (animation) under simulation run.

5.3. Hypothetical simulation

The proposed prototype system of PES can be used as a production simulator equipped with real control logics. Because most production simulations implement control logics within a simulation model, there must be a gap between an actual control decision and a simulated decision. On the other hand, the prototype system provides a direct interaction with a real execution control system for the production simulation model and, therefore, is able to function as a more practical simulation tool than other nonsimulation-based tools.

Table 4
Message specification.

Type	Item	Description
MHReq	Event	Event type of *LdReq* or *UldReq*
	Date	Current date
	EqpID	ID of equipment requesting material-handling for loading or unloading
	ContID	ID of a container required to be moved
	LotID	ID of the lot of WIP contained by the container
	ProcID	ID of the current process of WIP to be performed
DspEvent	Event	Event type of *DspCmd*, *DspStart*, or *DspEnd*
	Date	Current date
	LotID	ID of a lot dispatched to a target equipment
	SrcID	ID of the source equipment in which the lot is originally located
	FinID	ID of the target equipment in which the lot is to be finally located
MHEvent	Event	Event type of *MHCmd*, *MHReady*, *MHStart*, and *MHEnd*
	Date	Current date
	ContID	ID of a container under material handling
	LotID	ID of the lot of WIP contained by the container
	SrcID	ID of the source equipment in which the container is originally located
	FinID	ID of the target equipment in which the container is to be finally located
	CurEqpID	ID of current equipment in which the container is currently located
ProcEvent	Event	Event type of *ProcReady*, *ProcStart*, and *ProcEnd*
	Date	Current date
	EqpID	ID of equipment under processing
	LotID	ID of lot of WIP processed by the equipment
	ProcID	ID of current process of WIP
EqpEvent	Event	Event type of *EqpDown* and *EqpRcvr*
	Date	Current date
	EqpID	ID of equipment changing status

DspCmd, dispatching command; *DspStart*, dispatching start; *DspEnd*, dispatching end; EqpDown, equipment down; *EqpRcvr*, equipment recovery; *LdReq* load request; *MHEnd*, material-handling ready; *MHCmd*, material-handling command; *MHReady*, material-handling ready; *MHStart*, material-handling start; *ProcEnd*, process end; *ProcReady*, process ready; *ProcStart*, process start; *UldReq*, unload request; WIP, work-in-progress.

In this article, a simulation study is presented to demonstrate the interoperability of material-handling equipment with processing equipment within the proposed production automation framework. However, for confidentiality issues, a hypothetical data and production scenario (based on a realistic setting) were applied to our simulation study. The hypothetical simulation employs a unit pyroprocessing cell composed of two types of processing equipment: R for a unit process of STEP01 and CP for a unit process of STEP02. There are three pieces of equipment by type, all of which have identical processing capacity. In addition, a piece of material-handling equipment is used to connect the processing equipment. Here, a logistic problem on machine routing is posed, which is to select the next processing equipment of a WIP finishing STEP01 among the CP type of equipment. One possible routing strategy is to explicitly link an R type of equipment and a CP type of equipment for the shortest path material handling. However, because of fixed machine routing, a breakdown of either piece of equipment (e.g., R type or CP type) causes idle operation of the other type of linked equipment. Therefore, flexible machine routing is another possible strategy, as it allows a WIP to select among all CP types of equipment an available piece of equipment to perform STEP02. However, in this case, overall material-handling loads can be increased due to longer path material handling. Fig. 9 shows WIP flow according to two types of routing strategies (i.e., fixed routing and flexible routing).

Table 5 shows simulation results for full capacity production for 1 year in the hypothetical cell, assuming that the processing time of every piece of processing equipment follows an identical normal distribution with 48 hours of mean and 2 hours of standard deviation. It is noted that the constructed simulator is flexible and works with various statistical distributions. PlanMgr continually generates an initial WIP if a loading station of raw material is available. The number of replications for our simulation study was 20. The flexible routing strategy results in a higher throughput (1.77%) and a shorter lead time (1.09%) than the fixed routing strategy. According to a two-sample t-test, data sets derived from two routing strategies are significantly different from each other (i.e., p-value $< .05$). Consequently, we can conclude that the flexible routing strategy provides an improved productivity. In other words, the flexible routing strategy offset increased material-handling loads by enhanced machine utilization. Moreover, through the simulation study, material-handling request–driven collaborations between the processing simulation model and the material-handling simulation model were fully demonstrated and validated.

		Container information		WIP information					
Event	Date	ContID	prevContID	LotID	ProductID	ProcessID	SrcID	FinID	CurEqpID
MHCmd	20160101_000503	BASKET_01	NA	LOT_0001	REDUCTED	STEP01	LD01	R01	LD01
MHReady	20160101_000503	BASKET_01	NA	LOT_0001	REDUCTED	STEP01	LD01	R01	LD01
MHStart	20160101_001143	BASKET_01	NA	LOT_0001	REDUCTED	STEP01	LD01	R01	LD01
MHEnd	20160101_002503	BASKET_01	NA	LOT_0001	REDUCTED	STEP01	LD01	R01	R01
MHCmd	20160102_235000	BASKET_01	NA	LOT_0001	REDUCTED	STEP02	R01	CP01	R01
MHReady	20160103_000910	BASKET_01	NA	LOT_0001	REDUCTED	STEP02	R01	CP01	R01
MHStart	20160103_002050	BASKET_01	NA	LOT_0001	REDUCTED	STEP02	R01	CP01	R01
MHEnd	20160103_002910	BASKET_01	NA	LOT_0001	REDUCTED	STEP02	R01	CP01	CP01
MHCmd	20160105_004500	BASKET_U01	BASKET_01	LOT_0001	REDUCTED	OUTGOING	CP01	ULD01	CP01
MHReady	20160105_010140	BASKET_U01	BASKET_01	LOT_0001	REDUCTED	OUTGOING	CP01	ULD01	CP01
MHStart	20160105_011320	BASKET_U01	BASKET_01	LOT_0001	REDUCTED	OUTGOING	CP01	ULD01	CP01
MHEnd	20160105_012640	BASKET_U01	BASKET_01	LOT_0001	REDUCTED	OUTGOING	CP01	ULD01	ULD01

Fig. 6. Example of a material-handling history (LotID: LOT_0001).
MHCmd, material-handling command; MHEnd, material-handling end; MHReady, material-handling ready; MHStart, material-handling start; WIP, work-in-progress.

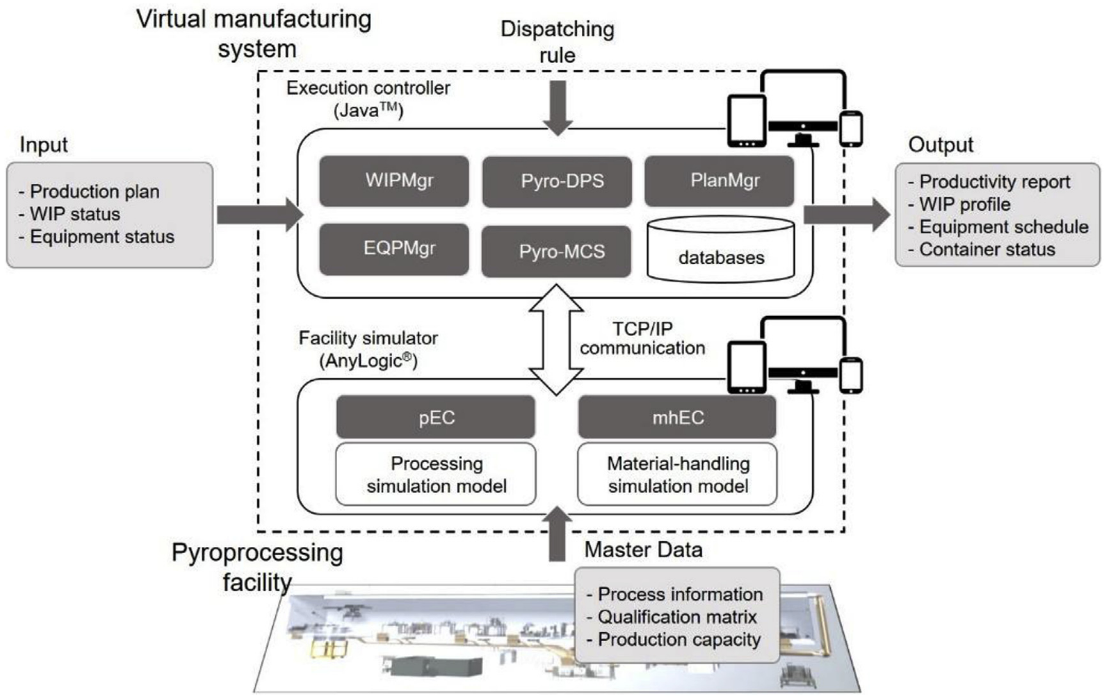

Fig. 7. System configuration of prototype system.
mhEC, material-handling equipment controller; pEC, processing equipment controller; TCP/IP, transmission control protocol/internet protocol; WIP, work-in-progress.

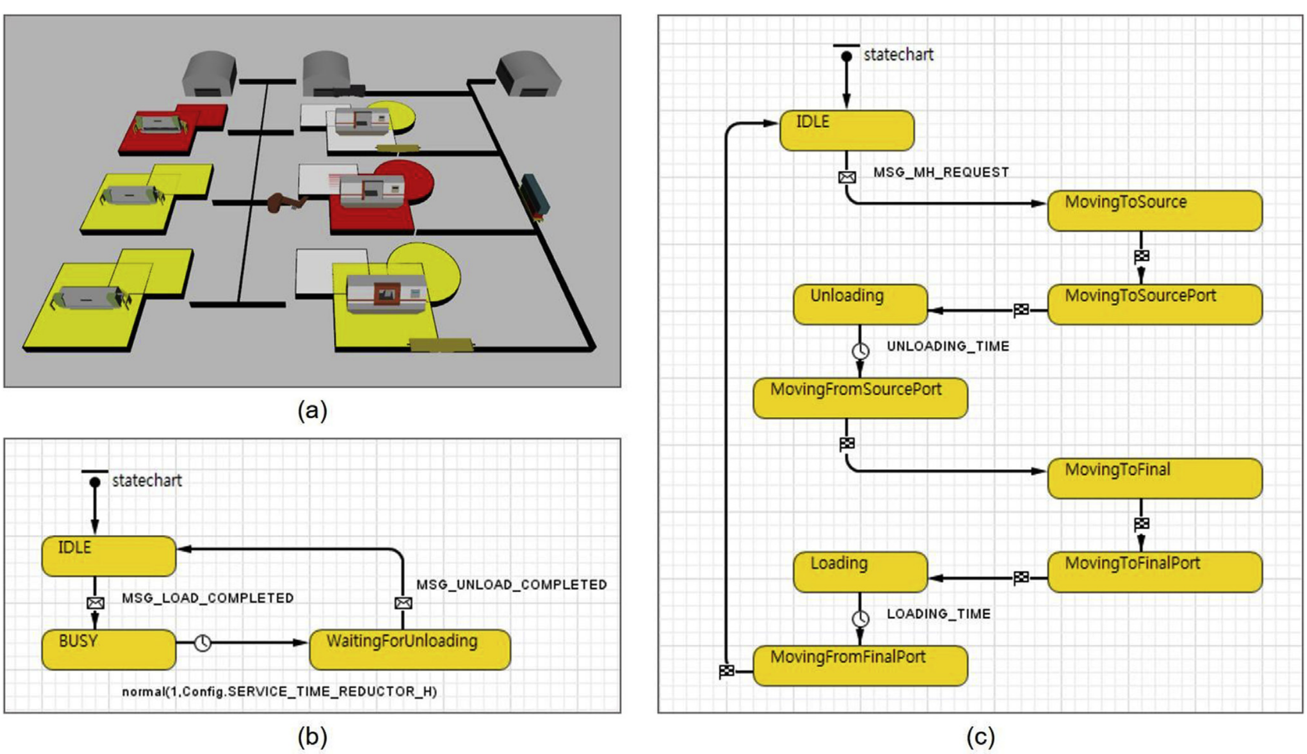

Fig. 8. Simulation model implemented in AnyLogic. (A) Graphical view (animation) under simulation run. (B) Processing model using statechart diagram. (C) Material-handling model using statechart diagram.
MSG, message.

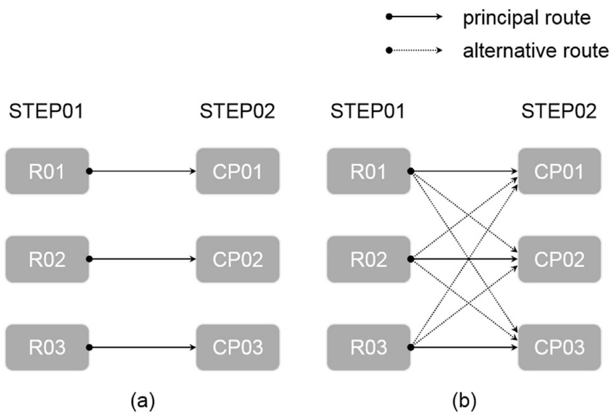

Fig. 9. Simulation scenarios. (A) Fixed routing. (B) Flexible routing.

Table 5
Simulation result (confidence level = 95%).

Criterion	Fixed routing	Flexible routing	*p*-value from *t*-test
Utilization of equipment R (%)	87.16 ± 0.32	88.96 ± 0.29	1.57052E-09
Utilization of equipment CP (%)	87.52 ± 0.23	89.04 ± 0.35	2.71019E-08
Throughput	410.30 ± 1.70	417.57 ± 1.94	3.34078E-06
Lead time (min)	6,295.18 ± 29.35	6,226.59 ± 26.75	3.01904E-03

6. Conclusions

The theme of this article was application of a production planning system and a control execution system for a radioactive facility. As a preliminary design for a supervising system for pyroprocessing, a manufacturing execution system intended for the pyroprocessing facility, named PES, was first proposed based on the investigation of the distinctive features of a pyroprocessing facility. PES is a dispatching-oriented execution control system that manages production operations as a link of an automated control system with a production planning system. Unlike an execution control system for conventional manufacturing systems (e.g., a flat panel display fab), the proposed PES employed a material-handling request–driven event model, rather than a process-tracking model, as an execution control mechanism. It was assumed that processing activity is triggered by a material-handling event denoting that WIP is loaded to the processing equipment. Moreover, the main functional modules of PES were implemented in a prototype system, which consists of an execution controller and a facility simulator. Interoperability between processing equipment and material-handling equipment was demonstrated via a hypothetical simulation study.

For further research, the interface of PES with a planning system (i.e., an external communication interface of PlanMgr) can be detailed to fully implement an entire production management system. Moreover, control mechanisms for processing and material-handling equipment should be developed which can implement sequential interactions between pEC (or mhEC) within PES and associated equipment, in addition to their communication protocol. Algorithmic development for decision-making beyond simple dispatching rules is also a possible future research direction. Finally, a look ahead mechanism for dispatching is another promising approach; this would consider future conditions of equipment and WIP within a predefined time window.

Conflict of interest

None.

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