A Study on NPP Construction Activity Numbering System for Level ⅣIntegrated Master Schedule

A Case Study for MMIS Field Design Changes

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***Abstract* — The Advanced Pressurized Reactor-1400 (APR-1400) Nuclear Power Plant (NPP) construction projects have a schedule hierarchy of Levels Ⅰ-Ⅳ, while a large portion of Level Ⅳ schedules refers to developing an Integrated Master Schedule (IMS) for each important target date. IMS is developed and used for the purpose of effectively managing the key milestone that must be achieved to ensure project success in the construction site. Level Ⅳ IMS should be developed while taking into account the specific conditions of each work process. Existing construction activity numbering system has an evident structure to provide clear instructions to develop up to Level Ⅲ Project Control Schedule (PCS), but Level Ⅳ is to be seen having a room to be improved. We investigate the existing construction activity numbering system by using a case study to find out if existing system can be expanded to be compatible with Level Ⅲ PCS. It also examines whether existing construction activity numbering system can be reflected according to specific conditions of MMIS field design changes without modifying the existing Work Breakdown Structure (WBS). Finally, we simulate the virtual schedule by using PRIMAVERA and verify that it is applicable to practical MMIS field design changes in NPP construction projects.**

Keywords* — *Construction Activity Numbering System, MMIS Field Design Changes, Nuclear Power Plant Construction Project, Schedule Management

I. INTRODUCTION

Installed nuclear capacity reached 392 GWe at the end of 2016, which is the highest level that has ever been reported. There are 447 operational nuclear power reactors in 30 countries, 16 countries have plans or proposals for building new reactors. The trend of Nuclear Power Plant (NPP) construction does not appear to be declining in worldwide [1].

The first Korean-designed Advanced Pressurized Reactor-1400 (APR-1400) went into commercial operation in Shin Kori 3 last December 2016; while Shin Kori 4 in South Korea and BNPP 1-4 in UAE are being currently constructed. Man Machine Interface System (MMIS), the entire digital Instrument & Control (I&C) system introduced in Shin Kori 3 & 4, had many field design changes even after delivery and installation. These MMIS field design changes actually have a significant impact on achieving key milestones; therefore, intensive schedule management is essential at that moment. In order to accomplish this kind of purpose, level Ⅳ Integrated Master Schedule (IMS) requires that well-structured construction activity numbering system, which can support the development of IMS, while taking into account the specific conditions of MMIS field design changes. However, the existing construction activity numbering system of Level Ⅳ IMS has been regarded as having limitation of compatibility with the existing Level Ⅲ Project Control Schedule (PCS) because specific instructions are not fully provided.

IMS is used extensively to achieve key milestones e.g., Initial Energization, Cold Hydro Test (CHT), Hot Functional Test (HFT), that are of greatest interest to executives of project management in NPP construction projects. Although many IMS have been developed and used in NPP construction projects, it has been seen that there is a limit to the construction activity number system that effectively supports them.

This study is important that it examines the construction activity numbering system that supports the development of the Level ⅣIMS for MMIS field design changes in the future NPP construction project. This will be of great help in intensive schedule management that plays an important role for achieving key milestones.

II. LITERATURE REVIEW

Previous studies on the APR-1400 MMIS was only focused on the development phase of design & manufacturing that had discussed (ⅰ) the full scope of the digitalized integrated verification test facility and completed verification test [2]; and, (ⅱ) the project experience of MMIS for component design, manufacturing and testing [3]. In addition, the development of Work Breakdown Structure (WBS) for the APR-1400 NPP has been studied, excluding observing and analyzing the construction activity numbering system [4]. Although the scheduling technique considering each specific conditions of the construction projects have been studied several times [5, 6], there has been no research on construction activity numbering system that supports the development of IMS, especially considering specific situations of the MMIS field design changes in NPP construction project. It has not yet been fully studied why the MMIS field design changes necessarily occur in the APR-1400 construction projects and whether the existing construction activity numbering system effectively supports Level ⅣIMS.

As a result, there have been research papers on the scheduling and MMIS, but this study is likely to be of great significance as no studies on improvement of construction activity numbering system have been reported to our best knowledge, from the perspectives of MMIS field design changes in APR-1400 construction projects. Therefore, this study aims to improve existing construction activity numbering system and contribute to more effective schedule management in future APR-1400 construction projects.

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III. RESEARCH METHODOLOGY

In this study, the scope is defined as the improvement of the construction activity numbering system applicable to the MMIS field design change. This is because MMIS, which was applied to the APR-1400 model as a whole for the first time, has been known from the experience that it needs a systematic schedule management; (i) the number of MMIS field design changes occurring during NPP construction is significant, and (ii) if these design changes are not completed, they will have a significant impact on other key milestones.

As illustrated in Fig. 1, this study begins with a case study of Barakah Nuclear Power Plant (BNPP) 1&2 construction project, a precedent project of APR-1400. Case studies are a useful way to investigate the practices of precedent projects. This is because it is fairly reasonable to study the problems of the current system and the corresponding improvements in light of the experience actually applied to the theory. In this perspective, case studies provide an opportunity to observe the existing system, and these fine observations can be useful in developing a yet to-be released, and a practically effective improvement model that can be directly applied in the field.

Our empirical data consists of actual precedent project materials. Concerning the validity and reliability of this research, the use of this type of archival records and documentation should be completed with other types of evidence, such as interviews for the purpose of triangular [7]. Therefore, direct experiences of the authors participating in the precedent projects were utilized together.

After discovering the limitations and disadvantages of the existing construction activity numbering system, we propose improvement by theoretical structure modeling considering its specific working conditions and processes. Results are verified through simulation.

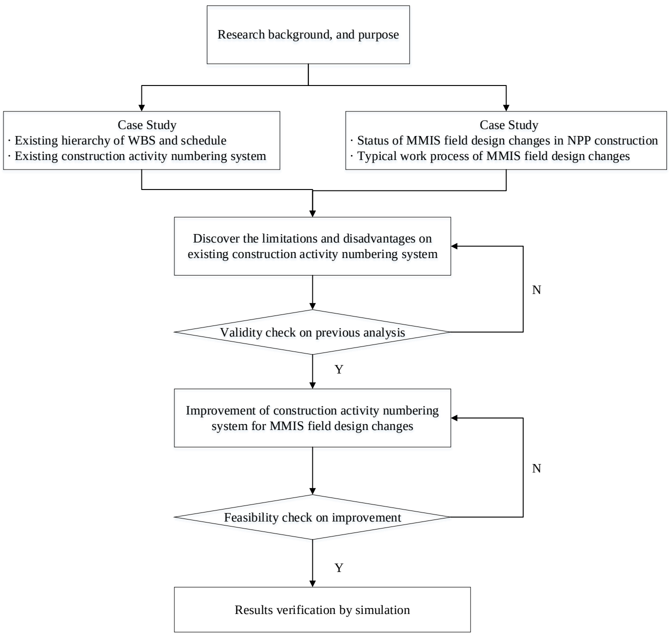

Fig. 1. Flow chart of research

IV. PRESENT CASE STUDY

A. *Existing hierarchy of WBS and schedule*

The WBS is a hierarchical decomposition of the total scope of work to be carried out by the project team to accomplish the project objectives and create the required deliverables. Each descending level of the WBS represents an increasingly detailed definition of the project work [8]. Fig. 2 presents the hierarchy of BNPP 1&2 construction project WBS, especially focusing on the construction sector. From Level Ⅰ to Ⅴ, the hierarchy was systemized and composed as follows: i) project name, ii) phase, iii) unit, ⅳ) Physical Breakdown Structure (PBS), and ⅴ) discipline. Under WBS Level Ⅴ, approximately 23,200 activities of BNPP 1&2 construction project were assigned to the relevant activity categories [4].

Fig. 3 shows that the BNPP 1&2 construction project has a schedule hierarchy of Level Ⅰ, Ⅱ, Ⅲ, and Ⅳ. As the top of the schedule hierarchy, Level Ⅰ is Project Milestone Schedule (PMS) that includes key milestones, and summary of the overall project schedule. Level Ⅱ is Critical Path Schedule (CPS) that agrees with the sequence of activities that represents the longest path through a project, which determines the shortest possible duration. Level Ⅲ is Project Control Schedule (PCS) that integrates network schedule including all activities from engineering, procurement, construction, and start-up; typically, PCS includes all work scopes in contract. Finally, level Ⅳ is the more detail schedules for working levels developed based on the PCS, and it should be reflected in Level Ⅲ. The detailed schedule in the construction sector includes the 8-Month Rolling Schedule (EMRS) and the 3-Week Daily Schedule (TWDS) [9].

Level IV schedule (e.g., ERMS, TWDS) is updated regularly; however, it is not used widely in the actual construction site. Because there are many parts that do not properly reflect the current field circumstances in the work process, and the interfaces with other work disciplines are not completely illustrated in the schedule. Therefore, to achieve the key milestones, IMS for each milestone are effectively prepared and actively operated by schedule engineers. In fact, there are many activities that are newly created during the

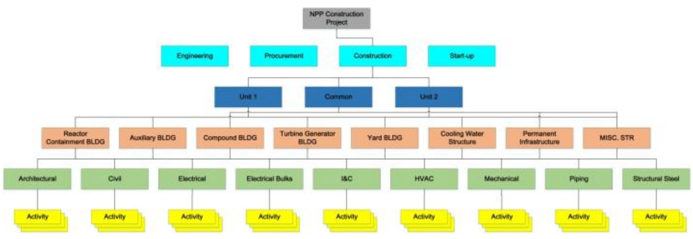

Fig. 2. Existing WBS hierarchy (construction)

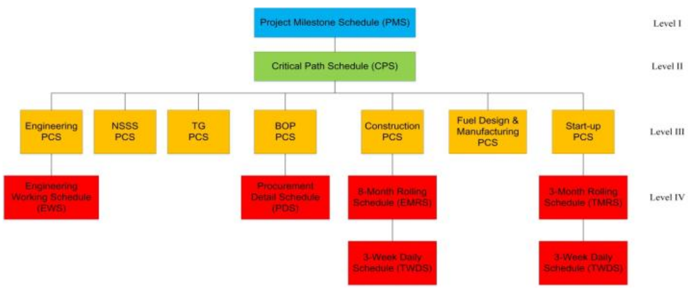

Fig. 3. Existing schedule hierarchy

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entire construction period, and these activities cannot be all identified in the both existing PCS and ERMS when implementing the MMIS field design changes in NPP construction. Therefore, developing the dedicated IMS has more benefits to manage the MMIS field design change works.

The simple evaluations on three IMSs acquired by the research are shown in the Table I below. Overall duration and the number of activities for each IMS are different. This clearly shows that IMS was created to achieve the target date, and the total duration and number of activities are not part of the judgment for IMS development.

B. *Existing construction activity numbering system*

Fig. 4 shows existing construction activity numbering system that has a hierarchy from Level I to V that defines unit, PBS, area, discipline, and sequence, respectively. As shown in Fig. 5, the PBS represents all elevations of buildings and structures for NPP as a numerical three-tiered breakdown. Depending on the building, the area is also the numerical breakdown as depicted in Fig. 6. At the end, the discipline indicates the construction activity type that varies from mechanical, piping, electrical, I&C, civil, architectural, and etc.

The following Fig. 7 is the existing structure for construction activity numbering system. The last 3 digits are the reserved place for the purpose of fitting detailed schedule whenever it is necessary. However, there is no specific instruction on how to apply it to IMS, and this is likely to cause confusion among project participants unless certain guidance is provided.

TABLE I. Example of IMS

Title	Duration (days)	Activity No.
Unit 1 Energization	677	564
Non-safety DCSC 2-4 (MMIS)	68	319
Unit 1 Cold Hydro Test	987	469

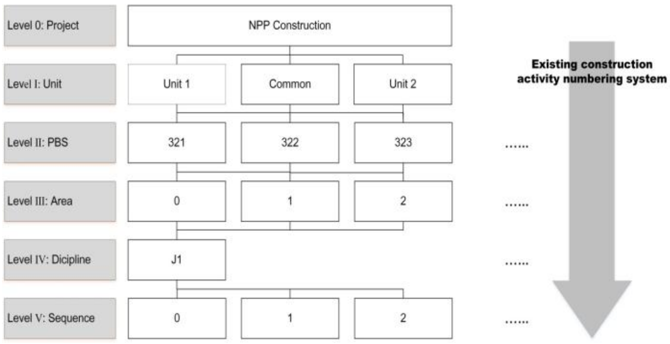


Fig. 4. Existing construction activity numbering system

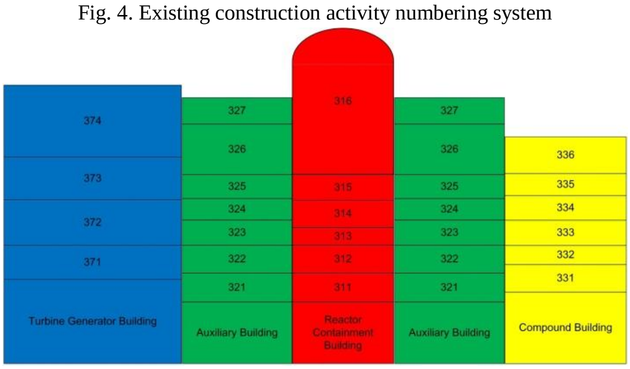


Fig. 5. PBS of NPP (APR-1400 model)

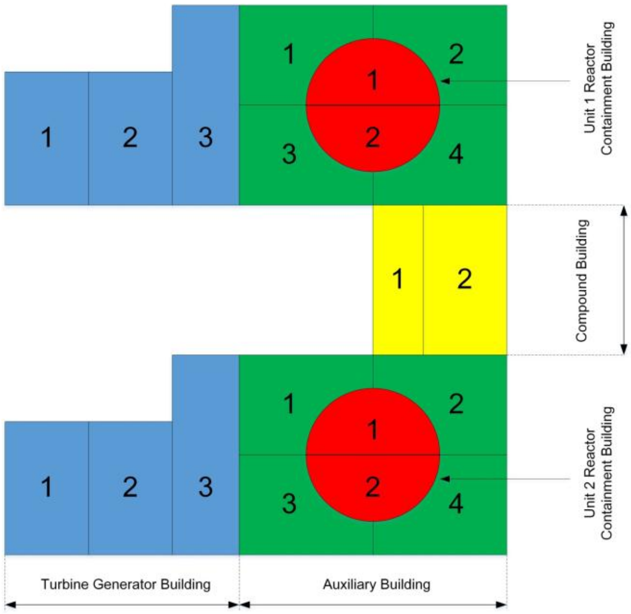
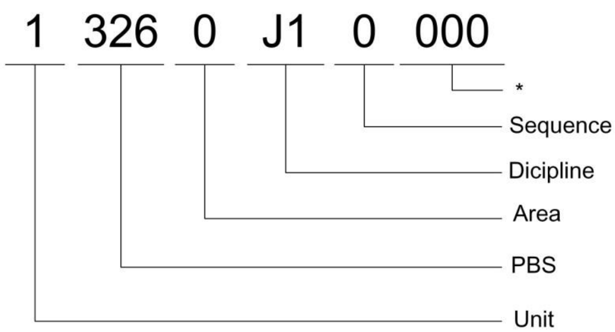


Fig. 6. General arrangement of NPP (APR-1400 model)



*: reserved for preparation of construction detail schedule

Fig. 7. Existing structure of construction activity numbering system

C. *Status of MMIS field design changes in NPP construction*

Table II shows the rate of changes after MMIS design freeze in BNPP 1&2. Total 40.6% design changes occurred in comparison with the design freeze version of drawings. This is closely related to schedule constraints. Fig. 8 illustrates in details why MMIS design changes should be implemented at the field; i) based on PCS, the final issue of MMIS design takes 30 months, and procurement requires 50 months of a lead time, ii) this means that if the MMIS goes into procurement with a final design, it will take a total of 80 months lead time, which significantly impacts achieving milestones of APR-1400 standard schedule, and iii) therefore, at some point (illustrated as a dashed line), design freeze is made to initiate manufacturing of the MMIS cabinets. It is advantageous from a project point of view to implement additional field design changes after installing the MMIS in the field with design freeze version.

TABLE II. Rate of changes after MMIS design freeze

Drawings Type	Rate of Changes per Drawings
C&ID	18.6%
CLD	40.5%
Display	63.0%

※These changes include all minor changes e.g., tag changes on the displays, adding jumper wirings, etc.

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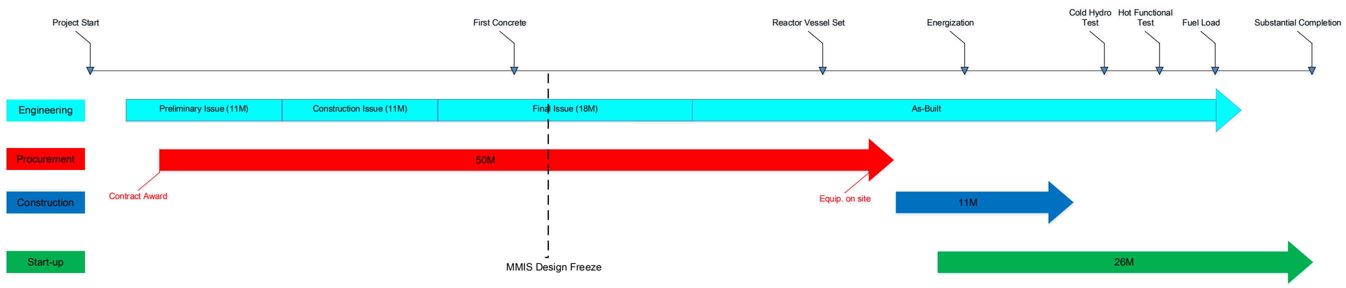

Fig. 8. Engineering Procurement Construction (EPC) and start-up schedule for MMIS in APR-1400 construction projects

V. IMPROVEMENT OF CONSTRUCTION ACTIVITY NUMBERING SYSTEM FOR MMIS FIELD DESIGN CHANGES

A. *Typical work process of MMIS field design changes*

As described in the Fig. 9, in order to implement MMIS field design changes from a configuration management perspective, a Design Change Package (DCP) and Start-up Work Request (SWR) documents are the first required. DCP refers to documents containing multiple design changes to equipment e.g., internal wiring, component replacement, software amendment, etc. The MMIS field design changes require additional works such as de-energizing cabinets, de-termination of control cables, in consideration of start-up testing interferences. Especially, the work duration and importance of software changes can be easily underestimated because none of disciplines e.g., civil, piping, include the same activities. Finally, once the software is loaded, work process goes through a regression test and cabinet energization to verify & validate the overall field design changes. Fig. 10 depicts Division of Responsibility (DOR) for each work process for MMIS field design changes.

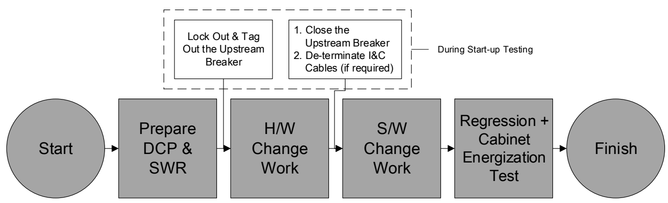

Fig. 9. Typical work process of MMIS field design changes

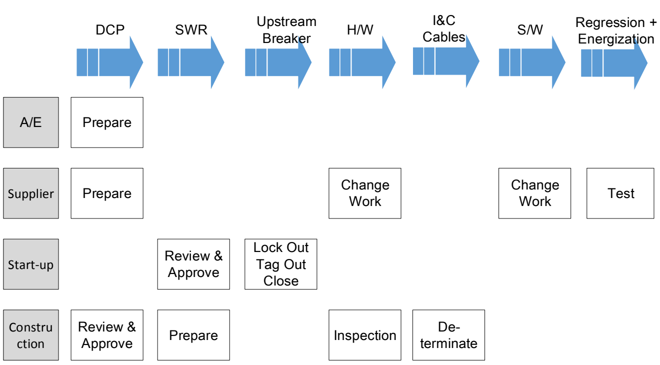

Fig. 10. DOR for MMIS field design changes

B. *Expanding construction activity numbering system*

As we have seen in Fig. 7, the current construction activity numbering system has only allocated 3-digits to support IMS, and does not provide specific instructions on how to use it. In addition, due to limitations of information that can be presented in only 3-digits, this seems to be a lot of difficulty in creating a practical level of detailed schedule. The current 3-digits are well linked to the existing Level Ⅲ PCS. However, readability for practitioners is relatively low, and above all, current construction activity numbering is not supporting to identify the DCP that are the starting point of MMIS field design changes. It also appears that the scope of MMIS field design changes is not directly taken into account.

Therefore, the improvement of the existing construction activity numbering system has been studied focusing on three key considerations as below.

1) *Compatibility with existing construction activity numbering system*

Code structures supporting Level Ⅳ IMS should interface with existing Level Ⅲ PCS. It is also important to consider whether the current existing construction activity numbering system can be improved without modifying the existing WBS as far as possible. Ultimately, both consistency and configuration are axes of being the top priority; it is most feasible to move toward improvement that expands the existing numbering system rather than further modifications.

2) *Design Change Package*

The primary purpose of MMIS field design change is to minimize the impact on other subsequent schedules. That is, a detailed schedule should be developed based upon prioritization of start-up testing support and each DCP work considering the urgency. Also, it would be more effective if there is readability so that practitioners can easily understand which DCP they are working on simply after identifying construction activity number.

3) *Single manageable control point*

Level Ⅳ schedule should tell exactly the details of work to be done. This is because the best workability can be achieved by taking into consideration of the worker's routes and convenience by buildings and their elevation. In this case, we determined that consolidating a single manageable point into the construction activity numbering system would improve practitioners' understanding of to-be field design change works.

Based upon the above three key considerations, this research propose the improved construction activity numbering system considering specific conditions of MMIS field design

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changes in NPP construction as shown in Fig. 11 below. The existing Level Ⅲ PCS is left as it is, and 3 expanded coding structures are added. The DCP number is assigned to the first coding structure, and the cabinet tag that is the work scope of the MMIS field design changes is assigned to the second coding structure. Finally, the third coding structure will be given to the sequence of field design change works for each MMIS DCP as earlier mentioned in Fig. 9, and it is expected to effectively support the actual work proceeding by technicians.

C. Verification through simulation test

Based on the above key considerations related to elements of compatibility, design change packages, and manageable point, we have developed a Level Ⅳ IMS with an expanded construction activity numbering system that reflects the characteristics of MMIS field design changes by using PRIMAVERA. Level Ⅳ IMS was created based on the expanded construction numbering system shown in Fig. 11 above, assuming that some non-safety systems of Unit 1 were meant to be changed on-site before the virtual CHT milestone. As described in Table Ⅲ, the total number of activities generated was 47, and the total construction duration was 110 days. No error was found in the simulation scheduling.

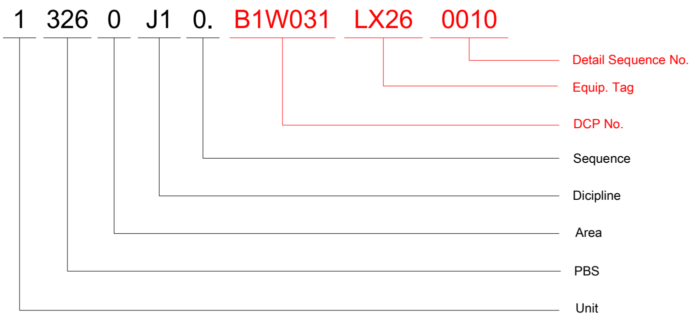

Fig. 11. Improved construction activity numbering system for MMIS field design changes

TABLE III. Simulation scheduling report

Scheduling/Levelling Report - 2-Aug-2017
==
Default Project...Simul
Projects:
Simulation: Expanding Construction Activity Numbering System for MMIS Field Design Changes

Scheduling/Leveling Settings:

General -------
Scheduling ....Yes
Leveling ....Yes
Ignore relationships to and from other projects ....No
Make open-ended activities critical ....No
Use Expected Finish Dates ....Yes
Schedule automatically when a change affects dates ....No
Level resources during scheduling ....Yes
Recalculate assignment costs after scheduling ....No
When scheduling progressed activities use ....Retained
Logic
Calculate start-to-start lag from ....Early Start
Define critical activities as Total Float less than or equal to .0
Compute Total Float As ....Finish Float
Calculate float based on finish date of ....Each project
Preserve scheduled early and late dates..........................Yes
Level resources only within activity Total Float.................No
Level Priority 1......................Activity Leveling Priority – Ascending
Level all resources...Yes

Advanced--------
Calculate multiple float paths..................................No

Statistics: -----------
Projects...1
Activities..47
Not Started...47
In Progress...0
Completed...0
Relationships...62
Activities with Constraint....................................4
Project: Simul Activity: MILESTONE0020 WMS, JHA, PTW Release (WEC, KEPCO)
Project: Simul Activity: MILESTONE0030 Materials for DCSC 2-4 Non-Safety System Receipt at Site (WEC)
Project: Simul Activity: MILESTONE0040 Factory Tested SW(DCSC 2-4) Available on Site(WEC)
Project: Simul Activity: MILESTONE0070 Unit 1 Cold Hydro Test

Errors:-------
Warnings:---------
Out-of-sequence activities......................................0
Activities with Actual Dates > Data Date.........................0
Milestone Activities with invalid relationships.................0
Finish milestone and predecessors have different calendars.......0

Scheduling/Leveling Results:----------------------------
Projects Scheduled/Leveled....................................1
Activities Scheduled/Leveled..................................47
Relationships with other projects.............................0
Data Date...31-Aug-2015
Earliest Early Start Date.......................................31-Aug-2015
Latest Early Finish Date..01-Feb-2016

Exceptions:-----------
Critical Activities...1
Project: Simul Activity: MILESTONE0070 Unit 1 Cold Hydro Test
Activities with unsatisfied constraints..........................0
Activities with unsatisfied relationships.......................0
Activities with external dates.................................0
Activities delayed due to predecessor delay.....................0
Activities delayed due to resource leveling.....................0
Activities that cannot be leveled...............................0

To organize and schedule activities, WBS configuration should be done first. Since the newly proposed expanded construction activity numbering system is designed to eliminate the need to modify the existing WBS, the existing WBS is applied to the simulation without any change. In addition, the related activities were constructed reflecting the working sequences of the MMIS field design changes identified in Fig. 9. While the existing construction activity numbering system was to represent units, buildings, elevations, areas, and disciplines; the expanded construction activity numbering system was sufficient to add the information of a specific DCP and the tag of cabinets to be design changed as shown in Fig. 12. The simulated Level Ⅳ IMS assumed (ⅰ) the priorities of the activities was determined by each urgency on start-up testing, (ⅱ) due to resources limit, only single work for DCP was allowed to be implemented. Since the simulation was intended to verify the scheduling using the expanded construction activity numbering system, the process of calculating the cost and quantity of the scheduling was not performed.

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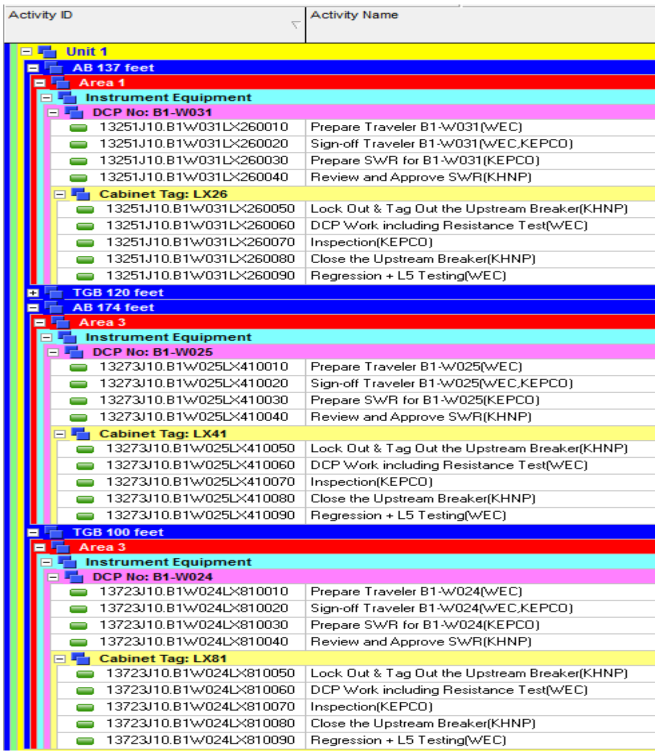

Activity ID	Activity Name
Unit 1	
AB 137 feet	
Area 1	
Instrument Equipment	
DCP No: B1-W031	
13251J10.B1W031LX260010	Prepare Traveler B1-W031(WEC)
13251J10.B1W031LX260020	Sign-off Traveler B1-W031(WEC,KEPCO)
13251J10.B1W031LX260030	Prepare SWR for B1-W031(KEPCO)
13251J10.B1W031LX260040	Review and Approve SWR(KHNP)
Cabinet Tag: LX26	
13251J10.B1W031LX260050	Lock Out & Tag Out the Upstream Breaker(KHNP)
13251J10.B1W031LX260060	DCP Work including Resistance Test(WEC)
13251J10.B1W031LX260070	Inspection(KEPCO)
13251J10.B1W031LX260080	Close the Upstream Breaker(KHNP)
13251J10.B1W031LX260090	Regression + L5 Testing(WEC)
TGB 120 feet	
AB 174 feet	
Area 3	
Instrument Equipment	
DCP No: B1-W025	
13273J10.B1W025LX410010	Prepare Traveler B1-W025(WEC)
13273J10.B1W025LX410020	Sign-off Traveler B1-W025(WEC,KEPCO)
13273J10.B1W025LX410030	Prepare SWR for B1-W025(KEPCO)
13273J10.B1W025LX410040	Review and Approve SWR(KHNP)
Cabinet Tag: LX41	
13273J10.B1W025LX410050	Lock Out & Tag Out the Upstream Breaker(KHNP)
13273J10.B1W025LX410060	DCP Work including Resistance Test(WEC)
13273J10.B1W025LX410070	Inspection(KEPCO)
13273J10.B1W025LX410080	Close the Upstream Breaker(KHNP)
13273J10.B1W025LX410090	Regression + L5 Testing(WEC)
TGB 100 feet	
Area 3	
Instrument Equipment	
DCP No: B1-W024	
13723J10.B1W024LX810010	Prepare Traveler B1-W024(WEC)
13723J10.B1W024LX810020	Sign-off Traveler B1-W024(WEC,KEPCO)
13723J10.B1W024LX810030	Prepare SWR for B1-W024(KEPCO)
13723J10.B1W024LX810040	Review and Approve SWR(KHNP)
Cabinet Tag: LX81	
13723J10.B1W024LX810050	Lock Out & Tag Out the Upstream Breaker(KHNP)
13723J10.B1W024LX810060	DCP Work including Resistance Test(WEC)
13723J10.B1W024LX810070	Inspection(KEPCO)
13723J10.B1W024LX810080	Close the Upstream Breaker(KHNP)
13723J10.B1W024LX810090	Regression + L5 Testing(WEC)

Fig. 12. Application of expanding construction activity numbering system

Fig. 13 shows the simulation scheduling by applying construction activity numbering system of the expanded concept shown in Fig. 11 without needs of changing the existing WBS shown in Fig. 2. In the end, by using PRIMAVERA to simulate the Level Ⅳ IMS that reflects the expanded construction activity numbering system, the research was able to confirm that (ⅰ) the specific conditions of the MMIS field design changes are reflected, (ⅱ) the existing Level ⅢPCS that assigned to a sub-level Ⅰ to Ⅴ of the existing WBS does not require further modification.

VI. DISCUSSION

Level Ⅳ IMS as an extension of Level Ⅲ PCS, has been widely developed in NPP construction projects as a detailed schedule that enables intensive schedule control for achieving key milestones that are of particular interests to project stakeholders, especially executives. It is well known that modifying the Level ⅢPCS whenever facing schedule changes is inefficient in terms of time and cost; therefore, intensive scheduling by developing IMS is a significant benefit to project management. This study has primarily focused on the benefits of expanding existing construction activity numbering system that supports IMS development.

This newly proposed construction activity numbering system is expected to be both more specific and highly readable than existing system, not only because it expands its coding structures but also there are considerations on (ⅰ) improving workability; (ⅱ) prioritization of field work to promptly deal with an urgency of supporting start-up testing; and, (ⅲ) removing uncertainties on generating new activity numbers on Level Ⅳ schedule. For example, activity number "13251J10.B1W031LX260050" easily provides the relevant information of unit, building, elevation, area, DCP, and field design change work scope of the cabinet. This new proposed construction activity numbering system does not only help technicians to easily understand the details of MMIS field design change works and its sequences; but also effectively support project managers and schedule engineers to meet the priority of construction work based upon urgency of start-up testing. In addition, this considers compatibility with existing system; it does not require modifying existing WBS and construction activity numbering system, which is beneficial in terms of time and cost.

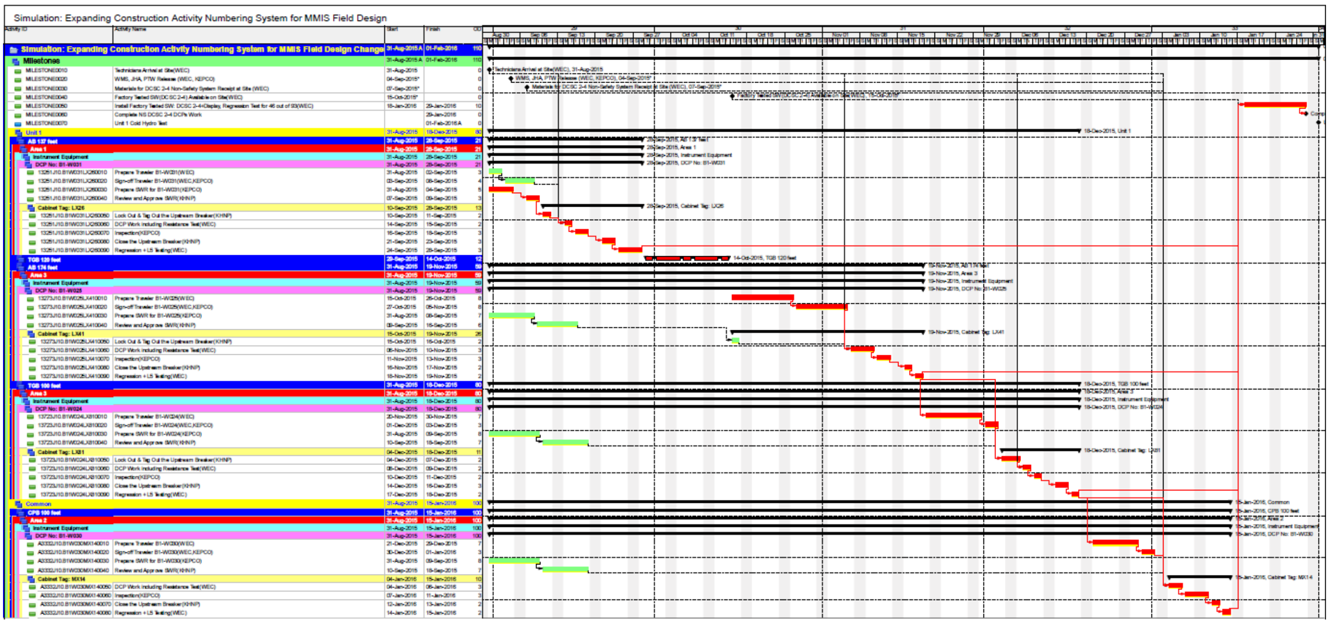

Fig. 13. Simulation scheduling by using PRIMAVERA

This expanding construction activity numbering system is expected to contribute to (i) standardization of Level Ⅳ IMS that can be applied to MMIS field design changes in new NPP projects; (ⅱ) improve the interface between the IMS and the existing Level Ⅲ PCS that currently has a tendency to play separately. Although this study discussed only the expanding construction activity numbering system applicable to MMIS field design changes, additional researches on the system applicable to IMS for other key milestones e.g., CHT, HFT, would be good follow-up studies.

We should also note that MMIS installation schedule in NPP construction project is fundamentally different from coal thermal power plant construction projects. A primary difference is that the safety class software Verification & Validation (V&V) and licensing process take a lot of time. It also has different interfaces with the other key milestones. Due to these technical differences and time constraints, MMIS field design changes are inevitable in current APR-1400 NPP construction projects. Therefore, more efficient construction activity numbering system is needed to support intensive schedule management.

This study is used to expand the construction activity numbering system. Although Level Ⅳ IMS has been used extensively to achieve key milestones in NPP construction projects, their construction activity numbering were being assigned at the discretion of schedule engineers, or limited 3-digits. These approaches tend to have very limited schedule information and are not comprehensive enough to standardize construction activity numbering system in NPP construction project based on the specific conditions of each work characteristics. As shown Fig. 14, the proposed construction activity numbering system presents not only overcomes these issues, but also offer compatible platform that can be easily applied to existing construction activity numbering system as well as existing WBS. We hope that the expanding construction activity numbering system for MMIS field design changes presented in this study will be an effective tool of schedule management for achieving the success of NPP construction project market, which is expected to increase from 2016 levels by 42% in 2030 [1].

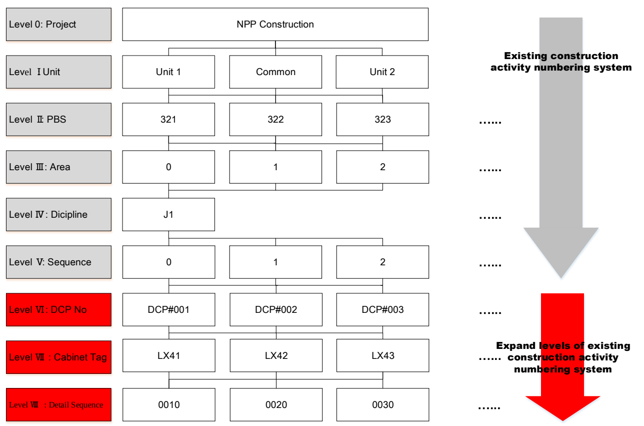

Fig. 14. Expanding levels of existing construction activity numbering system

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