Smart Lean Manufacturing in the Context of Industry 4.0: A Case Study

M. Ramadan, B. Salah

Abstract—This paper introduces a framework to digitalize lean manufacturing tools to enhance smart lean-based manufacturing environments or Lean 4.0 manufacturing systems. The paper discusses the integration between lean tools and the powerful features of recent real-time data capturing systems with the help of Information and Communication Technologies (ICT) to develop an intelligent real-time monitoring and controlling system of production operations concerning lean targets. This integration is represented in the Lean 4.0 system called Dynamic Value Stream Mapping (DVSM). Moreover, the paper introduces the practice of Radio Frequency Identification (RFID) and ICT to smartly support lean tools and practices during daily production runs to keep the lean system alive and effective. This work introduces a practical description of how the lean method tools 5S, standardized work, and poka-yoke can be digitalized and smartly monitored and controlled through DVSM. A framework of the three tools has been discussed and put into practice in a German switchgear manufacturer.

Keywords—Lean manufacturing, Industry 4.0, radio frequency identification, value stream mapping.

I. INTRODUCTION

THE complexity in today's manufacturing systems caused by recent changes in global markets and behavior of customer demands, where the products become highly customized with lower life cycles and shorter lead times, makes practicing lean more difficult and inefficient [1]. The kinds of rapid changes in the market's behavior lead to conflict with what lean is originally designed for [2]. For instance, the shorter product life cycle leads to continuous changes in terms of manufacturing processes, causing lean initiatives in such manufacturing systems to die over time, due to the lack of continuous care and supervision [3], [4]. In this regard, the lack of real-time visibility and monitoring systems complicates the situation, as the dynamic behavior of production systems is not captured [5]. Moreover, in traditional lean environments, the lean-based established instructions are not always followed by the workers due to lack of real-time sustaining mechanisms that enhance the practicing of lean instructions. As a result, there is a lack of systematic theory on the real-time control framework underlying lean manufacturing tools, specifically in the context of emerging technologies as in smart factories or Industry 4.0 [6]-[8]. For instance, [9] concluded that Industry

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4.0 and lean manufacturing supplement each other on a conceptual level, and then outlined how Industry 4.0 can support specific lean tools and practices to achieve lean targets. Where [10] attempted to emphasize the interaction between lean manufacturing and Industry 4.0, he proposes a methodology which provides guidance for Industry 4.0 under the lean production environment. In this regard, it is found there are several different definitions of Industry 4.0 [11]. Accordingly, Industry 4.0 can be defined as the usage of real-time captured data of smart entities which are involved in the manufacturing processes for real-time monitoring, analyzing, and thus controlling the interaction between them through the internet as well as making quick and efficient decisions [8].

In this work, a smart lean-based Industry 4.0 or lean-based smart factories framework called DVSM, as introduced by [12], is used as the lean-based IT platform. The main contribution of this paper is introducing a practical digitalization framework of the lean method tools, namely 5S, standardized work and poka-yoke to be smartly monitored and controlled in real-time through the lean-based IT platform, DVSM. The digitalization of these three lean practices will prompt the workers to follow lean instructions during production runs to enhance the leanness level in the manufacturing environment, where lean tools are mutually supportive to effectively reduce wastes [12].

The framework of smart 5S, standardized work, and poka-yoke was a part of the lean digitization project of a German switchgear manufacturing company. The target was to implement a smart lean system to reduce the Manufacturing Lead Time (MLT), maximize the value, and reduce the cost.

This paper is organized as follows: Section II introduces the integration between DVSM and the targeted lean tools. Section III-V address the three frameworks of digitalized lean tools 5S, standardized work, and poka-yoke, respectively. Section VI discusses a case study where the three lean tools have put in practice in a switchgear manufacturer. Finally, Section VII summarizes and concludes the article.

II. SMART LEAN-BASED MANUFACTURING SYSTEM

The last decade's improvements in traditional lean manufacturing are almost done independent of any support of the recent advancements of information technology [13]. However, the powerful features and recent rapid advancements in real-time data capturing systems as well as ICT can strongly help lean practitioners to build a smart lean-based manufacturing system through using the recent technological solutions such as Cyber-Physical Systems (CPS) and the Internet of Things (IoT) as key components of

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Industry 4.0.

Such technological solutions facilitate the integration between Industry 4.0 and the lean manufacturing system to achieve better performance and reinforce lean implementation that adapt to recent market changes in order to strengthen the competitive edges of manufacturing companies. In this regard, still there are few research efforts addressing how lean manufacturing benefits from ICT to achieve the smart-lean based system, also referred to as Lean 4.0. It can be expressed as "built in lean Industry 4.0" or lean-based Industry 4.0. For instance, [14]-[18] addressed the digitalization of lean manufacturing and the possibilities to be integrated with industry 4.0. However, from the technical point of view, most of these studies mainly focus on the organizational level rather than practical description of digitalization of lean tools and practices. Few studies like [19]-[21] introduced how Industry 4.0 can enhance VSM through the real-time collection of data. For instance, [18] introduce the concept of "Value Stream Mapping 4.0" (VSM 4.0) to give the opportunities to digitally upgrade their lean production system through product flow tracking. Reference [19] propose a real-time VSM system that can assist companies in their lean implementation by automatically creating value stream maps. In the same context, [22] present a novel intelligent value stream-based food traceability cyber physical system approach integrated with enterprise architectures. However, the recent studies were limited on computerizing the VSM through product tracking rather than develop a computerized smart lean tool in order to be automatically implemented during the production run based on real-time controlling algorithms.

The basis of this section is to introduce a systematic integration between the DVSM and the targeted lean tools to contribute toward lean-based Industry 4.0 or lean-based smart factories. The DVSM is used as the IT enabler of lean tools and practices where the time-based products flow is greatly emphasized, which is considered as the most important success factor of lean [12]. As [12] suggests, DVSM can be defined as

"a computerized event-driven lean-based IT system that runs in real-time according to lean practices and tools to monitor and control all manufacturing aspects to effectively reduce wastes and maximize value".

An overview of the DVSM components is depicted in Fig. 1.
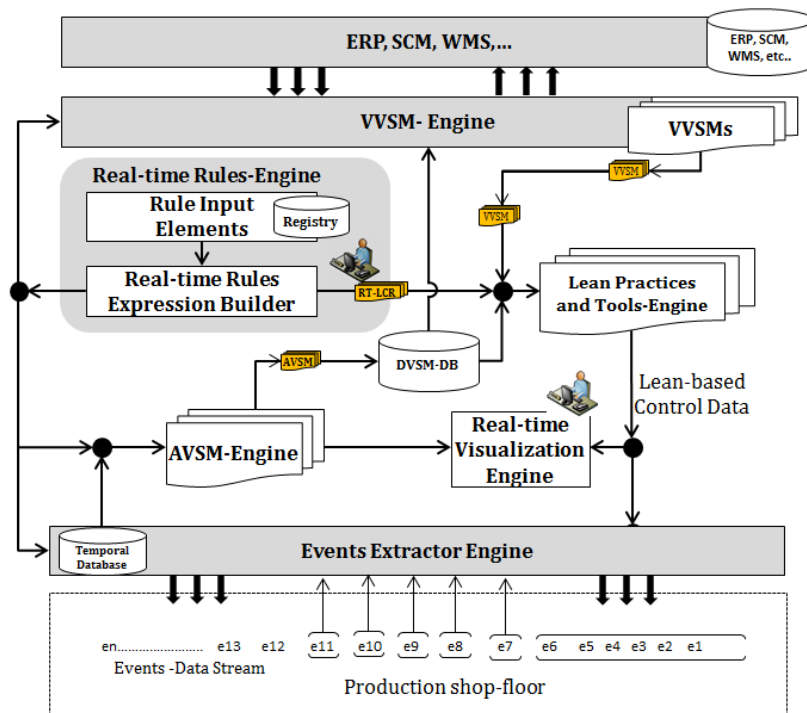

Fig. 1 Overview of Components of the DVSM for Lean 4.0 [12]

To maximize the target of DVSM in any manufacturing environment, a RFID system must be systematically installed on that manufacturing environment in order to reach the maximum level of real-time data capturing with highest accuracy. In this context, a RFID must be installed to cover all production areas to achieve a smart or intelligent manufacturing environment. But due to the nature of some manufacturing environments, RFID cannot always secure a high level of real-time visibility of the manufacturing environment; in these cases, additional RFID-supportive technologies can be applied to support RFID in data collection such as Wireless Sensor Networks (WSN), digital cameras, 2D-barcodes, automation devices, Programmable Logic Controllers (PLC), or any technological solution. In the worst case, if the real-time event cannot be automatically captured, the lean practitioners are prompted to use the workers to enter event-related data through the Touch User Interface (TUI) [12].

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After the manufacturing environments become smart, the DVSM become ready to enhance any lean tool. The smart upgrade of lean tools and practices starts through construction the suitable Real-Time Lean Control Rules (RT-LCRs) with the help of a Real-Time Rules Engine (RT-RE). In this engine, lean specialists can use the Real-Time Rules Expression Builder (RT-REB) module to build with the assistance of the "Rule Input Elements" (RIE) module any RT-LCR. The constructed RT-LCRs are uploaded on Lean Practices and Tools Engine (LPTE) to run in real-time. During the production, the RT-LCRs of the targeted tools namely, 5S, standardized work, and poka-yoke utilize real-time production data in Actual Value Stream Mapping (AVSA) which represents the actual status on the production line and the DVSM-Database to smartly monitor and control the targeted lean tool according to the standard lean-based environment which is represented by Virtual Value Stream Mapping (VVSM).

III. SMART 5S METHODOLOGY

One of the main challenges facing lean success and sustainability is the return to the old way of working. The lean tool 5S is negatively affected due to these kinds of challenges. One of the main causes is the lack of real-time monitoring and controlling technique that prompt the worker to follow the designed work instructions to sustain 5S and keep it alive for long term. In this regard, there have been few studies investigating how the Industry 4.0 concept will impact soft lean tools, such as 5S, Kaizen, standardized work, teamwork, workforce involvement and autonomy. These so-called soft practices are crucial, not only for achieving high performance through lean manufacturing, but also for sustaining lean performance in the long term [23].

In this section, a framework of a smart-5S mechanism is introduced to keep manufacturing area constantly organized to support other lean tools through avoiding frequent production incidences and interruptions that are caused by a chaotic workplace, and thus reduce MLT. The digitalization process of 5S starts based on the traditional transformation of 5S. The following steps describe systematically the upgrading of smart-5S:

1stS "Sort": In this stage all unnecessary items or tools which are not required on a regular basis in each workplace along the value stream should be removed. After that, the remaining items and tools will be converted to become smart tools through attaching them with the RFID-tag, and thus become trackable during the production run. For more accurate real-time data collection, the tool-boards or any other tools holder can be equipped with sensors to detect the tools' relevant event-instances, especially pick-up-return events in terms of time. This step will enable the DVSM to track each tool and thus detect the exact time of usage (i.e. start/end-events), identify the point of use (i.e. location/s), and determine in which value stream state the smart-object/tool has been used (i.e. processing-state, transport-state, etc.).

2edS "Set-In-Order": After the unnecessary objects were eliminated and the remaining tools and items become smart, in

Set-In Order stage, the smart-tools will be located in the right place at the right workstation according to different practical aspects. At the virtual level, the smart-tools will be defined with full description in the RT-RE in DVSM in terms of location and the expected event-instances such as pickup-event/return-event this will be saved also in the global-VVSM, since it represents the virtual world. As a result, all smart-tools/objects become physically and virtually assigned to a specific workstation or route.

3rdS, 4thS, and 5thS "Shine, Standardize and Sustain": These 3S are combined in one stage, since they are physically practiced during the production run to achieve the target of *"5S"* of keeping the workplace thoroughly organized. For instance, the *3rdS "shine"* and 4thS *"Standardize"* can be digitalized through construct standard RT-LCRs of the best practice of the 3rdS that encourages the worker to keep the workplace clean after certain processing stages and ensuring that every smart-object is returned to the right place after each use during the daily production run. The 5thS *"Sustain"* is uploading the RT-LCRs on the LPTE in DVSM and updating them for any changes. These RT-LCRs are running during the production to keep the best practices in 3rdS and 4thS alive and prevents the workers to return to the old way of working. These steps are depicted in Fig. 2.

To achieve the best results, technical experience is important to construct each RT-LCR of 5S. Since lean tools are mutually supportive to reduce wastes, the lean tool *"standardized work"* is taken into consideration while constructing the RT-LCRs.

The RT-LCRs of 5S are constructed based on the potential incidences on the lean environment. The following are some possible scenarios: If the sequence of the defined processing-tasks in VVSM are interrupted or mixed, if a specific tool is not returned after usage to the right place (i.e. the tool board) which it belongs as defined in the VVSM, if a tool is misplaced inside/outside the workstation to which belongs as defined in VVSM, if the time to return a tool to the tool board overrides the standard time as defined in VVSM, and if a wrong tool is picked up from the tool board to execute the next processing task as defined in the VVSM according to lean tool "standardized work", which is discussed in the next section.
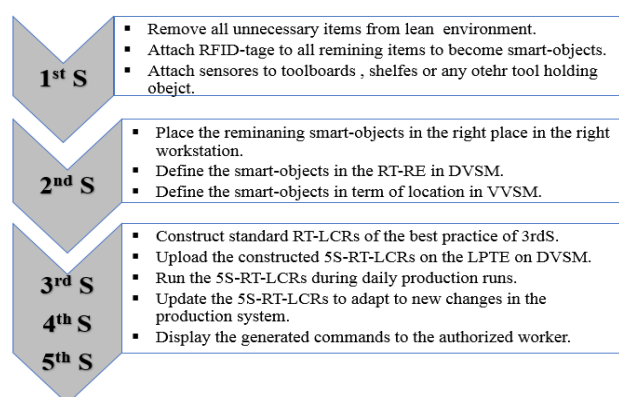

	• Remove all unnecessary items from lean environment.
1st S	• Attach RFID-tage to all remining items to become smart-objects.
	• Attach sensores to toolboards , shelfes or any otehr tool holding obejct.
2nd S	• Place the reminaning smart-objects in the right place in the right workstation.
	• Define the smart-objects in the RT-RE in DVSM.
	• Define the smart-objects in term of location in VVSM.
3rd S	• Construct standard RT-LCRs of the best practice of 3rdS.
4th S	• Upload the constructed 5S-RT-LCRs on the LPTE on DVSM.
	• Run the 5S-RT-LCRs during daily production runs.
5th S	• Update the 5S-RT-LCRs to adapt to new changes in the production system.
	• Display the generated commands to the authorized worker.

Fig. 2 Development stages of a Smart-5S for Smart Lean System

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Another suggested scenario regarding the life-cycle of the tools, if the life-cycle of a specific tool is finished as defined in VVSM or it is broken, then it will be reported and automatically eliminated from the registry of the RT-RE and a "*replenishment command*" is generated prior to life ends or directly after it is broken to prevent the interruption due to the lack of the required tool. To explain the working mechanism of the RT-LCR of 5S, the following simple RT-LCR is constructed based on complex event processing technique representing two scenarios.

Definitions for RT-LCR "5S"

T_i	Smart-Tool with unique RFID-tag i
VVSM-P_{ix}	Virtual status of P_{ix}
P_{ix}	Product i-x
SW_{ix}	Standard work of P_{ix} defined in VVSM-P_{ix}
WS_i	Workstation i
TB_i	Tool-board i
L_x-TB_i	Smart locations in TB_i
P_i-Ee_s,e_e	Processing task "i" starts/ends events
AVSM-P_{ix}	Actual value stream of Product i
E_{Pxi} e_A,e_D	Arrival/departure of P_{ix} on WS_i
PO_i	Production Operator
T_i -E_{Rei}	Return event of tool T_i
$T_{r.t}$	Return time of T_i after each P_i-Ee_e in VVSM

RT-LCR$_i$ = 5S-Misplaced Tool

01:	**IF** P_{ix}-e_A to WS_i
02:	**Then** [VVSM-P_{ix}] **display** SW_{ix} to PO_i
03:	**Check** P_i-Ee_e -P_{ix}
04:	**IF** "T_i" $\neq$ L_x-TB_i within "$T_{r.t}$"
05:	**THEN SEND** to PO_i **[Return = "T_i =L_x-TB_i"]**
06:	**IF** $[\neg T_i$ -$E_{Rei}]$ detected **AND** P_{i+1}-Ee_s
07:	**THEN SEND** to PO_i **[Return = "T_i =L_x-TB_i"]**
08: END	

Line 01 if the arrival-event of P_{ix} is detected at workstation WS_i **Line 02** then the DVSM will monitor the SW_{ix} standard work steps for the authorized production operator PO_i **Line 03** checks the end time of each step P_i-Ee_e **Line 04** if the used tool is not returned within defined time in VVSM-P_{ix} **Line 05** generates a command for the authorized PO_i to return it before the next step starts **Line 06** if the event of returning the used tool is NOT detected and the next processing step Pi-Ee_s is started **Line 07** generates "Return command" to PO_i. **End.**

The RT-LCR enhances the operator interaction with lean instructions to keep the workplace organized after each processing step or stage. The smart-5S should work in combination with other lean tools such as standardized work. Smart standardized work is addressed in the next section.

IV. Smart Standardized Work–SSW

The development of Smart Standardized Work (SSW) starts with defining the best practice of the executing process's steps along the value stream; this done with the help of motion study and work design principles. During this stage of digitalization, a product's information such as equipment, tools, used machine, and workers along value stream will be invoked from the VVSM of the corresponding product. After all processes' steps for each product are defined, lean practitioners construct the VVSM and save it in the VVSM engine in event-context. Then they start with the help of the

RT-RE to construct the RT-LCR of each product-state along the value stream, the constructed RT-LCRs will be uploaded on LPTE. The VVSM as event-context represents the optimal manufacturing sequence and used as a reference for RT-LCRs running on LPTE to smartly monitor and control the flow and execution of manufacturing steps during the production run. The digitalization process is described in Fig. 3. The working principle of SSW on the LPTE is explained in the following RT-LCR.

Definitions for RT-LCR "SSW"

P_{ix}	Product i-x
VVSM-P_{ix}	The virtual status of P_{ix}
AVSM-P_{ix}	Actual value stream of Product i
SW_{ix}	Standardized work of P_{ix} defined in VVSM-P_{ix}
$E_{SW\text{-}ix}$	Even-context of SW_{ix}
WS_i	Workstation i
TB_i	Tool-board i
P_i-Ee_s,e_e	Processing task "i" starts/ends events
E_{Pxi} e_A,e_D	Arrival/departure of P_{ix} on WS_i
PO_i	Production Operator
C_i	Generated commands

RT-LCR$_i$ = SS-Sequence of processing steps

01:	**IF** E_{Pxi} e_A to WS_i
02:	**Then** [VVSM-P_{ix}] **display** SW_{ix} to PO_i
03:	**Check for** $E_{SW\text{-}ix}$ [$E_{SW\text{-}ix}$ -VVSM-P_{ix} = $E_{SW\text{-}ix}$-AVSM-P_{ix}]
04:	**IF** [$E_{SW\text{-}ix}$ -VVSM-P_{ix} $\neq$ $E_{SW\text{-}ix}$-AVSM-P_{ix}]
05:	**SEND** [C_i] to PO_i
06: END	

Line 01 detects the arrival of product P_{ix} to workstation WS_i **Line 02** displays the defined work sequence to the PO_i in his local computer **Line 03** and **Line 04** checks for any discrepancies between the virtual work sequence in VVSM-P_{ix} and the actual steps being executed and tracked in AVSM-P_{ix} **Line 05** generates the most suitable command that already defined in the VVSM-P_{ix} to avoid any type of wastes. **END.**
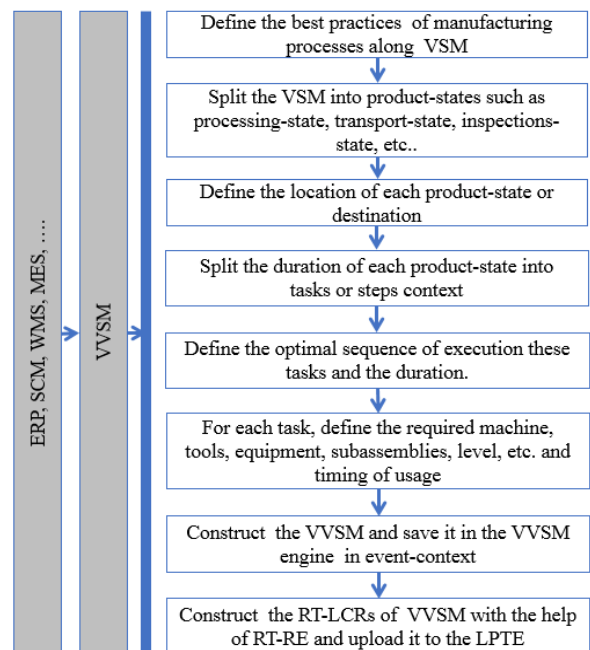

Fig. 3 Development of smart standardized work in DVSM

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The production operators are enabled to interact with the manufacturing process through DVSM-TUI. For example, they can confirm "task-start" and "task-finish" states before and after each task. The timestamps of tasks will ensure that the production operator follows the standardized work step by step. The timing information are important for further analysis like check the work progress and the expected time to finish, make performance curve analyses, find the root causes of incidences through aggregation of events over a period of time, find improvement opportunities, etc.

V. SMART POKA-YOKE

Poka-yoke uses different methods and techniques like mechanical mechanisms to achieve zero-defects and reduce the wastes. However, in certain situation these methods and techniques are not always feasible, costly, and even complicate the process. Therefore, this part introduces a new a smart poka-yoke based on production real-time information as an alternative and more effective techniques to smartly avoid defects and errors. The smart poka-yoke is considered as real-time validation mechanism though building RT-LCRs that use the actual production data collected in AVSM and the virtual production data in VVSM to automatically notify the production/assembly operators about occurrence of potential failure in advance, moreover smart poka-yoke send notification if an error was occurred to prevent forwarding it to the downstream workstations. So, smart poka-yoke works to prevent the propagation of errors to next workstations and thus avoid more wasteful activities in term of extra processing-time, rework, or scrap. Development of a smart poka-yoke extremely depends on the type of manufacturing process. In this paper a general framework concerning quality issues in assembly lines is introduced. Fig. 4 describes a general methodology to develop a smart poka-yoke mechanism. Smart poka-yoke works in combination with both SSW and smart-5S. For instance, to develop a smart poka-yoke in assembly production lines; the Bill of Materials (BOM) of specific product (P_i) is already uploaded to the product's VVSM in SSW stage in term of location and right sequence. The lean practitioners construct poka-yoke RT-LCRs to detect the potential of failures and errors. During assembly processes, the RT-LCR detects *"Assembly start/finish-event"* and constantly compare between the assembled smart-items in AVSM and the standard items in VVSM through aggregation of related events. If they AVSM-P_{ix} match VVSM-P_{ix}, then the product will be conveyed to the next workstation, otherwise a notification will be sent to the assembly operator to fix the problem. This RT-LCRs will check all assembled smart-items along the value stream to ensure that all and right subassemblies have been assembled. With combination with SSW, another smart poka-yoke RT-LCRs can be constructed to ensure that the right smart-tools are used to perform certain manufacturing tasks. This is because using the wrong tools leads to failures or quality problems. For example, due to substantial similarities between some tools, the operator may use the wrong thread cutting taps that have the same diameter but different pitches. Additional poka-yoke RT-LCR concerning assembly operation can be expressed to prevent the problems from its origin. For example, to prevent replenishment of wrong subassemblies to side-line inventory, a smart poka-yoke RT-LCRs can be expressed to detect the arrival of wrong subassemblies. In this way, more time is saved before the error is detected during or after assembly and thus reduces the maximum amount of wastes. Other smart poka-yoke RT-LCRs can be constructed to prevent wrong setting of production parameters on the smart-machines (e.g. temperature, speed, surface roughness, wrong cutting tool is fixed, depth of cut, etc.). Where the VVSM-P_{ix} checks the setting on machine M_i once the arrival-event of specific products is detected on M_i, and if any discrepancies are detected then the production operator will be notified.
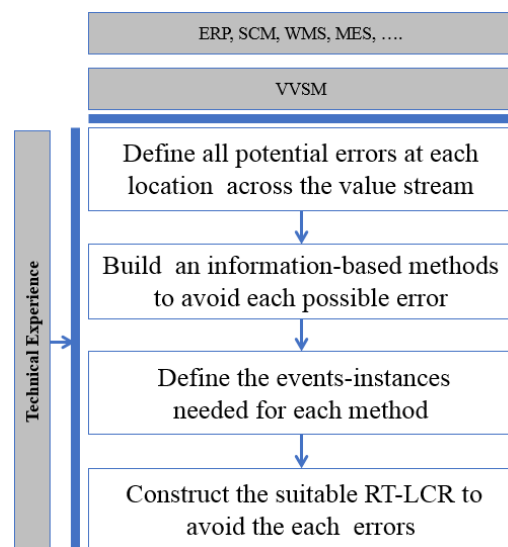

Fig. 4 Development of Smart Poka-Yoke in DVSM

VI. CASE STUDY -SMART 5S, SSW AND POKA-YOKE

The introduced concepts of smart lean tools have been put into practice in a switchgear assembly line to reduce wastes and enhance the lean environment. The assembly line is characterized by a high-mix/low-volume production environment. The facility layout includes different production and assembly workstations, which start with the welding workstation where the steel-compartments are produced with four different models. The steel-compartments are the main part of the switchgear. The finished steel-compartments are conveyed using Electrified Monorail System (EMS) to the assembly workstation it belongs to.

Each switchgear model consists of several small components and subassemblies with big similarities between them for each model. The components and subassemblies are conveyed using shelf trolley to replenish the side-line inventory and the subassemblies trolley. The side-line inventory contains the common components, while the subassemblies trolley contains highly-customized subassemblies, depending on the current switchgear is being assembled.

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In an assembly station, the operator assembles all subassemblies inside the steel-compartment; then, it is closed and transported to be filled with SF$_6$ gas. Finally, the switchgear will be transported to the testing station. Before, during and after assembly, there are different types of incidences and problems made by workers. For example, some tools are frequently forgotten inside the steel-compartment, the execution of frequent wrong assembly due to substantial similarities between subassemblies for each model which are visually hard to distinguish, the logistic operator often replenishes subassemblies to the wrong station, convey steel-compartments to the wrong assembly station, and used tools are repeatedly lost or misplaced, because the replenishment is a paper-based work; papers during replenishment of subassemblies are frequently lost, the assembly workers do not follow the right sequence of performing the assembly tasks, and routes between workstations are repeatedly blocked with different types of objects like a hand pallet truck. In addition to incidences during assembly, the duration of assembly tasks is not standardized, which adversely impacts the variability in the overall production system. This interrupts the lean tool "line balancing".

The target of this case study is to develop a nontraditional mechanism to avoid the mentioned interruptions and incidences to enhance the lean environment in the assembly area. Therefore, it is proposed to develop smart lean mechanisms based on real-time production information supported mainly by RFID. Since, most of the incidences are quality-related problems, a smart poka-yoke mechanism is considered as the major tool, while smart-5S and SSW working are the supporting tools. To do so, many steps have been proposed to convert the assembly environment to a smart area, where all objects become smart and trackable in real-time. Initially, install the RFID system to cover all of the assembly area to provide 100% real-time visibility. Attach steel-compartments with the RFID-tag and define in the DVSM as the ID of the finished switchgear, since it is the main part of it. The company requests that all suppliers attach the RFID-tag to all components and subassemblies, so as to become smart-objects and trackable in real-time. Convert all internal items to smart-objects through the attached RFID-tag to all movable and stationary items in the assembly area such as hand tools, equipment, hand pallet truck, forklifts, logistic and assembly operators, etc. The locations of tools in the tool boards are equipped with a displacement sensor to detect the existence of the tools and the related events like pick up/return events.

For smart real-time monitoring and controlling of the smart assembly area, the event-instances of all smart-objects must be defined and saved in the registry of the RT-RE to be used for building the RT-LCRs and tracked during the assembly activities. To build the AVSM of each product, the product-driven events along the value stream of each type of switchgear should be defined. The value stream, starting from welding until testing of the switchgear, has been split into event-instances through steel-compartment arrival/departure-event instances. The arrival/departure-event instances are used

to track the flow of the switchgear along the value stream and build the AVSM with all product-flow related data like timing of all executed activities during each product-state and the assembled components. This can be done by building complex events though the aggregation of primitive-events. In this case, all primitive events (i.e. event-instances) related to each product-state should be defined such as the arrival-event of subassemblies at side-line inventory, or tool pick up/return-event from/to tool board, etc.). The predefined production and assembly-related data of each switchgear should be translated into event-context and uploaded to the VVSM engine. It is noticed that, the more event-instances we define, the more accurate real-time monitoring and controlling we obtain.

The next stage is to construct the RT-LCRs concerning smart poka-yoke, SSW, and smart 5S. In this regard, several RT-LCRs have been proposed to prevent the interruptions, reducing rework through avoiding quality errors, reducing the duration of assembly tasks, and thus reduce the MLT. Some of these RT-LCRs are narratively introduced as follows:

RT-LCR-1 smart poka-yoke-detection of wrong subassemblies: once the assembly-state starts, through detecting the arrival-event "E_{eA}" of the switchgear at the assembly station, the defined sub-assemblies in VVSM will then be displayed on the TUI at this station with the best sequence of tasks which represent SSW. Once assembly-state end is detected (i.e. though conformation of worker using "task-finish" button using TUI), the RT-LCR-1 checks with the help of VVSM if the right subassemblies have been assembled. Finally, the RT-LCR-1 generates the departure-event "E_{eD}" to be executed by EMS. Since the hand tools are not listed as subassemblies in the VVSM, they are then considered as "wrong subassemblies", and therefore, the RT-LCR-1 can be extended to involve the forgotten hand tools inside the steel-compartment. Thus, if a hand tool is detected after "E_{eD}", then RT-LCR-1 generates the "stop-command" to EMS to prevent forwarding the steel-compartment to the next stage at the same time the worker will be notified to fix the problem.

To prevent problems from its origin, the supportive RT-LCR-2 is proposed to support RT-LCR-1 to prevent the replenishment of wrong subassemblies to both subassemblies trolley and side-line inventories as well as ensures JIT-replenishment. RT-LCR-2 checks, prior to the "arrival-event" of next switchgear, the required subassemblies from VVSM and generates the "replenishment command" to the logistic operator. RT-LCR-2 checks the subassemblies once the "departure-event" from storage area is detected as well as once "arrival-event" of the shelf trolley detected at assembly station. If any "wrong subassembly" is detected, the logistic operator will be notified.

RT-LCR-3 is SSW rule to enhance the assembly operators to follow the right sequence of assembly tasks according to standardized work. If RT-LCR-3 detects the "arrival-event" of a steel-compartment, then according to VVSM, the sequence of the standardized tasks with all work instructions will be displayed on TUI. Since the operators are enabled to interact with DVSM, the start/end of each task can be detected through

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press "*task-start*" and "*task-finish*" button before and after each task respectively. In this way, RT-LCR-3 checks if the assembly operator follows the right sequence and it can generate certain commands to guide him to optimum work sequence. RT-LCR-3 can be updated from time to time for farther improvements.

RT-LCR-4 is proposed to support RT-LCR-1 and RT-LCR-3 through smart 5S that prompt the assembly operators to return the smart tools to the tool board after each use. Since each tool board is equipped with a displacement sensor system, in RT-LCR-4 the "*removal-event*" of a specific tool must be synchronized with the detection of the "*task-start*" in RT-LCR-3; if the wrong tool is detected which is not required to perform this task, the worker will then be notified in order to prevent failures. Through the sequence of detected "*removal-events*" of tools from the tool board, the wrong sequence of tools required during the same task can be detected and reported. After the task is finished, if the last used tool is not needed in the next task, then it should be returned to the tool board. The next task will not be displayed if the assembly operator did not press "*task-finish*". The same issue, if the "*return-event*" is not detected for that tool after "*task-finish*" event is detected, then the next task will not be displayed until "*return-event*" is detected. Finally, after finishing the assembly activities, RT-LCR-4 checks prior "*departure-event*" if all tools are returned to tool board; otherwise, the RT-LCR generates a "*stop command*" to EMS to stop the forwarding of the switchgear to the next station. This way prompts the assembly operators to keep the assembly station organized. The event-instances of all incidences are proposed to be saved in a database of DVSM for further offline analysis. For example, it can be used for waste analysis and to find improvement opportunities.

These RT-LCRs contribute toward the smartness of a production system concerning lean targets, where the MLT of a switchgear is expected to be reduced through avoiding all time-wasting events.

VII. Conclusion

This study aimed to revolutionize the lean paradigm by benefiting from the recent advancements in ICT systems to create an extended real-time lean enterprise to adapt to the latest changes in global markets. Since lean tools are mutually supportive to effectively reduce wastes and maximize value, a future work is to upgrade all smart lean tools to be integrated within DVSM. For further improvements, a smart real-time waste system can be developed to detect the root-causes of the seven types of wastes in real-time to anticipate failures in advance to avoid them and reduce their negative impacts on the overall leanness level. A complex event compiler could be developed for RT-RE in DVSM to check the code validity of RT-LCRs according to the information in the meta-data, as well as to conduct syntactical and lexical analysis and corrections of the RT-LCRs. Finally, DVSM can be integrated with simulation software to enable lean practitioners to investigate the consequences of proposed scenarios or critical decisions in advance to prevent causing serious disruptions.

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