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# A Learning Roadmap for Digital Lean Manufacturing

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**Abstract.** Since it was popularized in the 1990s, the adoption of lean production has been a primary driver for continuous improvement efforts worldwide. The next wave of industrial improvement is widely considered to be driven by industry 4.0 and digitalization. This has more recently led to the emerging concept of digital lean manufacturing. In this paper, we address a shortcoming in the extant literature, which presents an abundance of roadmaps for digitalization but very few addressing this in combination with lean. As such, we present a learning roadmap for digital lean manufacturing, with a core focus on cybersecurity. The roadmap has been developed and tested by combining theory with practical insights at the Norwegian Catapult Lean4zero Lab, Norway's first and only full-scale digital lean simulator.

**Keywords:** Lean Manufacturing; Digitalization; Cybersecurity

## 1 Introduction

Lean manufacturing emerged as an alternative way of organizing and managing manufacturing enterprises in the 1990s [1]. Since then, lean principles have been applied in countless organizations across many industries. More recently, the emergence of Industry 4.0 and its associated advanced digital technologies has presented manufacturers with more novel ways of optimizing production operations [2]. Subsequently, the combination of lean with Industry 4.0 has since resulted in the emergence of Digital Lean Manufacturing (DLM) systems [3]. Given that the manufacturing industry in general, and small- and medium enterprises (SMEs) in particular are at a state of low maturity in terms of combining advanced digitalization with existing lean initiatives, in this paper we present a learning roadmap for realizing the potential benefits of DLM, which can be used for taking a company from an initial state to an advanced level of innovation and cooperation. We adopt a particular focus on cybersecurity (an important part of digital transformations which is unfortunately often overlooked in research and in practice [4]), and build the roadmap based on practical insights from SINTEF's *Lean4zero Learning Lab* in Raufoss, Norway.

## 2 Theoretical background

In this chapter, we present relevant theory in order to shape a theoretical frame for the investigation.

## 2.1 Industry 4.0

There is a general industrial trend towards *Industry 4.0*, which brings new optimization possibilities via the application of advanced digital technologies. [5] presents an overview and classification of Industry 4.0 (I4.0) as nine technologies that are transforming industrial production; Additive Manufacturing, Augmented Reality (AR), Autonomous Robots, Big Data Analytics, The Cloud, Cybersecurity, Horizontal- and Vertical Integration, Industrial Internet of Things (IIoT) and Simulation. [6] attempts to frame these technologies within the context of *smart supply chains, smart manufacturing, smart products and smart working*. The impacts of *Artificial Intelligence* (AI) are discussed, e.g. implying that using AI technology reasonably and effectively can greatly promote valuable creativity and enhance the competitiveness in both humans and machines [7].

In order to start the development towards I4.0, manufacturing companies are expected to apply digital communication platforms and integrate their value chains, sharing data in and between cyber-physical production systems [3]. These developments imply that machines and control systems, so called *Operational Technology* (OT) that are otherwise not originally designed to be exposed on the Internet, are suddenly connected to *Information Technology* (IT) solutions and made available via cloud services, which creates a vulnerability. Companies should therefore count on becoming the target for cyber-attacks and in addition to making preventive measures, become reactive enough to keep the economic loss at a level as low as possible in case of an eventual attack [8].

## 2.2 Lean Production and Digital Lean Manufacturing

Lean production is based on the principles and working processes of the Toyota Production System (TPS) and has been defined as *doing more with less* [11]. In its simplest terms, lean production can be described as the elimination of waste [12]. [13] provided the world with a vision of what lean is about, summarizing lean thinking as five principles: (1) precisely specify value; (2) identify the value stream for each product; (3) make value flow without interruptions; (4) let the customer pull value from the producer; and (5) pursue perfection. More recently, there have been indications that lean thinking and practice is better described as a learning system than a production system [14]. For example, [15] suggests that "*improvement without learning is not lean thinking*".

Digital Lean Manufacturing (DLM), refers to the application of digital technology, such as e-Kanbans, digital problem solving, and kaizen in digital collaborative environments, in order to enhance the lean and learning transformation in manufacturing organizations [16]. Both [17] and [18] present Lean Production in the context of Smart Manufacturing, presenting the main components of a smart production system as *smart products, smart operators, smart machines, smart workstations and smart planners*, and subsequently comparing and contrasting these with Just-in-Time (JIT) and Jidoka and JIT, Total Quality Management (TQM), Total Productive Maintenance (TPM) and Human Resource Management (HRM), respectively. In fact, there is a significant emerging extant literature that covers the combination of lean production and digitalization, identifying various levels of lean and digital integration

[c.f. 3, 19, 20-23]. Studies of ERP systems from a lean perspective show that contemporary ERP systems can be used to support lean production by offering an array of support functionality for each of the five lean principles [24].

### **2.3 Maturity Models and Roadmaps**

Maturity models (MMs) enable users to identify the need for change and to derive the necessary measures to accompany the change process [25]. Several MMs and roadmaps exist for the implementation of both lean and digitalization. For example, [26] presents a MM for assessing I4.0 readiness and maturity of manufacturing enterprises, while [27] presents a capability MM for lean implementation in the context of ERP system integration in SMEs. The overview of Industry 4.0 MMs presented in [25] and based on a literature search comparing 11 different MMs, shows a variety in the number and definition of stages, spanning from 4 to 8 stages, e.g. initial, managed, defined, integrated and operability, and digital-oriented [28], or digitalization awareness, smart networked products, the service-oriented enterprise, thinking in service systems, and the data-driven enterprise [29], with an average of 5,3 and a median of 5 stages. Each of these MMs have more than one dimension, covering e.g. process, monitoring and controlling, technology, and organization; and business, application, information and technical infrastructure.

## **3 Research Approach**

This is a conceptual paper based on a literature review in combination with new insights drawn from a single case study, in which the authors were actively involved in the development of the *Lean4zero Learning Lab* – Norway's first and only full-scale training centre for DLM.

### **3.1 Case Description**

The *Lean4zero Learning Lab*, hereinafter referred to as "the lab", situated in Raufoss, at one of Norway's first catapult centres, the *Manufacturing Technology Norwegian Catapult* (MTNC), was first opened in August 2009 as a full-scale analogue lean manufacturing simulator. In response to demand from the Norwegian manufacturing industry, efforts began in 2019 to convert the simulator to a DLM learning lab.

The lab today offers courses with a mix of theoretical and action-oriented elements, training course participants in lean principles. The course material is based on lean management and the methodology and tools for efficient pull-based and levelled production with continuous improvement at its core. The courses span from one to three days, including Toyota Kata and learning organization, as well as value stream analysis, aiming at making course participants ready to independently manage lean-focused work when they return to their own organization.

### 3.2 Towards a Learning Roadmap for Digital Lean Manufacturing

As a result of the comparison of the 11 I4.0 MMs mentioned in the previous chapter, we suggest a five stage MM with the following predominant phases as the basis for the development of our Learning Roadmap for DLM:

1) Basic: Actuators and monitoring; 2) Data and system integration: Sensory and information processing; 3) Communication system: Network, interpretation and services; 4) Enhanced performance: Adaption and optimization; 5) Advanced innovation: Innovation and cooperation.

In the Learning Roadmap for DLM, measures for lean, advanced technology and cybersecurity are mapped to these five stages, giving the model a three-dimensional structure, using the environment in the lab as a practical example.

## 4 Discussion

In the next sections we will discuss the five stages identified in the MM above and present structured insights toward a Learning Roadmap for DLM.

### 4.1 Basic

The first stage of the Learning Roadmap for DLM describes an initial stage in a manufacturing environment, illustrated by the initial setup in the lab, from an advanced technology, lean and cybersecurity point of view. The current level of digitization is at a basic *actuators and monitoring* level, in the lab case comprising touch screens at each station for documenting the process and a program that produces statistic graphs, using the data collected via the touch screens, demonstrating the flow balance principles, by visualizing the takt-time and time spent on each station and product.

The Lab is a lean environment; the workplaces with parts and materials are organized based on 5S principles, the operations are standardized and described on standard operation paper sheets, the production is levelled and based on pull principles, and continuous improvement work is manually performed on analogue boards, based on manually gathered data analysed by humans. This environment describes the foundation on which the next I4.0 stage can be built, as digitalizing and automating a system that isn't lean makes only for digital waste [3]. Opening the door to the connected global world should be done after having a risk assessment system in place.

Not having connected any devices to the Internet, the level of technical cybersecurity measures at this stage includes e.g. basic virus protection on the computers, photo documentation control, and checking and limiting physical admission into the building. The organizational cybersecurity and safety management, is as important as the technical aspect, including continuous risk assessment management work being built-in in the continuous improvements work and including test execution of the risk handling plan, e.g. fire and loss of power supply drills, with roles and responsibilities clearly distributed in the organization.

## 4.2 Data and system integration

In the data and system integration stage of the Learning Roadmap for DLM, the focus is on *sensory and information processing*. At this stage sensors will be introduced in product and process in the Lean Lab, collecting data that will be used in the analysis process of the progress and quality. The parts are here made traceable, providing input to a digitized parts and material flow management, connected to sales and production planning information, through integrating off-line ERP and digital Kanban systems in a digital model of the business. The flow and quality performance data are in this stage being processed digitally and presented on digital continuous improvement boards and *manufacturing planning and control* (MPC) platform pads. At this stage, the *Lean4zero Learning Lab* will introduce cooperative, industrial and transport robots in the production, having them perform simple tasks. In this stage the systems are still not connected to the outer world, but service people installing and upgrading the robotic and digital systems might connect these to the Internet while working. Thus, with robots working in the area it will be important to have these organized in sub-systems, creating a basis for a layered system architecture including a definition of the human place within the system, such as e.g. the Purdue Enterprise Reference Architecture described in [30], having the safety and cybersecurity risk assessment level based on identification of safety issues and business value. There should be worst case scenarios identified and a communication and handling plan for all of these in place.

## 4.3 Communication system

In the communication system stage of the Learning Roadmap for DLM, *network, interpretation and services* are lead words. During this stage the digital flow within the *Lean4zero Learning Lab* becomes a link in a larger digital flow inside the value chain, including suppliers on one side and customers on the other. A communication platform is established, adding information from outside the organization to the internal data, digitally analysing and interpreting the available data, and communicating the results both internally and externally in the value chain. This means that input from customers and suppliers regarding e.g. the quality of the product or delays in the supply chain, will become input to the MPC, be interpreted by the system and trigger continuous improvement actions and changes in the production plan in the ERP system, performed by the human staff. *Virtual Reality* (VR) and *Augmented Reality* (AR) will be introduced as communication tools between the digital and robotic systems and the humans, e.g. instructing the existing or new human staff on new or existing operations. Cybersecurity measures will have to be considered here, e.g. isolation of networks at the different architecture layers of the business, securing that only the highest communication platform level is accessible over the Internet and that the lower levels, including the ERP system level, is guarded by several firewalls. The risk assessment and crisis handling plan should be updated with the cybersecurity risks deriving from connecting the business systems to the Internet. On a technical cybersecurity level, data on normal performance could be gathered, as part of the self-diagnosis of the system, reporting and sending out alarms at identified abnormalities.

#### **4.4 Enhanced performance**

In this stage the data processing is lifted to the next level, to some extent letting the system *adapt and optimize*, using a digital twin of the *Lean4zero Learning Lab* with simulation models to test possible scenarios and the possibility to automatically optimize the systems accordingly. Changes in customer needs, supply capacity or internal changes, e.g. machine service or human resource capacity, will hereby be integrated in the dynamic production planning, based on machine learning, and communicated to the human staff. Cybersecurity risk assessment analysis and handling plan will be updated continuously as part of the continuous improvement work, cybersecurity measure will be prioritized based on the outcome of the analysis, and the system will be stress tested.

#### **4.5 Advanced innovation**

In this stage of the Learning Roadmap for DLM, the systems and human resources are integrated in *innovation and cooperation* activities. In achieving stage five, lean and cybersecurity measures and countermeasures will become a cohesive part of the system. The robots, digital systems and humans in the lab will perform based on the output from secure data processing in the digital twin, possibly including e.g. diagnosis, prognosis and trial-and-error functions as described in [31], self-organizing in robust human-machine sub-systems, solving their tasks in dynamically optimized ways, e.g. by the deployment of human-in-the-loop hybrid-augmented intelligence systems. Suggesting such a model for safety and security issues, [7] argues that hybrid-augmented intelligence can provide strong technical support and a basic infrastructure framework to meet the increasing challenges in those security areas. It is there recommended to have humans participate in prediction, detection and subsequent disposition, making full use of human intelligence in complex problem judging and of AI in processing massive data.

### **5 Conclusion**

In this article, we adopt the stance that manufacturing firms should learn how to systematically combine lean thinking and practice with advanced Industry 4.0 technologies in order to build competitive advantage in the digital era. We present a five-stage Learning Roadmap for DLM distributed across three critical dimensions. These important elements have emerged from a literature review as well as from practical insights in developing a *Lean4zero Learning Lab*.

We suggest that this article has implications for both theory and practice. Firstly, with regard to theory, we present a framework that promises to evolve Lean Production towards an advanced human-machine innovation and cooperation system, through the creation of a flexible, autonomous and self-optimizing system. By adopting the Learning Roadmap for DLM, practitioners can begin to understand how to identify and take the next step on the DLM journey.

In terms of limitations, though the Learning Roadmap for DLM has been developed based on a literature review, practical experiences are based on a single case study in

the *Lean4zero Learning Lab* environment. Future research should therefore further develop and test the model in practice, as well as expand the cybersecurity analysis, specifying its different perspectives across the five levels.

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