Proceedings of the 2023 ASME International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2023
August 20-23, 2023, Boston, MA, USA

DETC2023-116759

ADAPTING DIGITAL TWIN FRAMEWORKS TOWARD LEAN MANUFACTURING FOR THE CIRCULAR ECONOMY

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ABSTRACT

Lean manufacturing is based on data collection and analysis that is used toward reducing waste and enabling continuous improvement. However, little research has been done bridging emerging topics of a Circular Economy and Digital Twins to lean manufacturing systems. A lean enabled manufacturing digital twin can provide more efficient interactions between these stakeholders and lean activities. Building on previous literature and the ISO 23247 standard–the Digital Twin Framework for Manufacturing– this paper identifies functional requirements for the adaptation of lean manufacturing to a digital twin model. The requirements are defined in terms of a multiple layers of the system: physical space, cyber-physical storage, primary processing, models and algorithms, analysis, feedback, and interfaces. To correlate a lean digital twin framework to the current standard effort, we identify the digitized-lean requirements that can be applied to standards in reference to ISO 23247. In practice, the digitalization of lean manufacturing can improve top-down management recognition, aid decision making, increase cost efficiency, sustain continuous improvement, enhance worker engagement, and support communication with stakeholders. Furthermore, the lean-adapted digital twin framework introduced and subsequent requirements can help interface lean to smart manufacturing systems, and apply standard lean principles to sustainability initiatives such as the Circular Economy.

1 INTRODUCTION

The growing interest in transitioning toward circular economy models has invoked a series of challenges put forth by global incentives to better the triple-bottom-line impact of the systems that create, use, and dispose of manufactured goods. The Circular Economy (CE) is defined as an economic system that facilitates total reduction in waste of resources coupled with value-added activities that ensure that resources retain their value and circulate within the manufacturing economy indefinitely, thus decoupling economic growth from resource depletion [1]. Earlier work towards sustainable manufacturing often limited the scope to improving specific products or production processes or, more generally, to a cradle-to-grave lens. The transition toward a CE is a systems-based approach that coordinates many economic actors to facilitate a cradle-to-cradle scope for manufacturing resources. Recently, manufacturers have made efforts to establish industrial symbiotic relationships [2], create closed-loop material lifecycles [3], and otherwise explored waste reduction practices for the transition toward a CE [4].

Another way to reduce manufacturing wastes is through implementing lean manufacturing principles. Lean tools, such as value-stream mapping, describe rudimentary proto-symbiotic relationships between suppliers, manufacturers, and consumers. As such, precursor ingredients for facilitating the transition toward a CE can be found in lean applications. Lean manufacturing, a widely-applied methodology, provides a foundation that can be integrated with CE approaches to transition from current production models toward a circular manufacturing system.

Lean Manufacturing (LM) is a systematic approach applied by manufacturers to identify and eliminate waste in the production sequence through continuous improvement in the pursuit of perfection [5]. LM maximizes production efficiency by facilitating a robust push-pull system that values just-in-time manufacturing where raw resources and finished products are not in surplus. Fundamentally, LM is built around communication and capabilities for forecasting supplier stock and customer demand. The lean-inspired connections from different lifecycle areas can provide a foundation to increase the interoperability and enhance the relationships between the material supply, manufacturing, and consumer lifecycle areas.

LM methodologies need modern advancements to remain competitive in industry 4.0 and transition to a CE. Lean manufacturing tools are applied manually in iterative approaches to facilitate the continuous improvement tenant of LM. The manual nature of LM applications requires specific lean management teams, worker buy-in, and enterprise culture to succeed. LM systems can fail over time due to corporate fatigue and high lean application costs in the pursuit of applying lean continuous improvement [6]. Furthermore, the conventional lean methodology is sparse in prediction and proactive methods that help identify whether manufacturing changes are impactful. Consistently marginal changes in manufacturing processes can increase costs outweighing the benefits to the system. Lastly, the conventional methods support little participation from the supplier and consumer lifecycle areas that must be accounted for in the transition toward a CE.

Applying lean principles toward a CE requires a digital transformation of lean methods that can allow for better interoperability, prediction capability, and lean system efficiency. Specifically, Digital Twin (DT) methods are well suited for representing, simulating, predicting, and guiding the physical interactions between lean applications and manufacturing systems. International Organization for Standards (ISO) defines Manufacturing DTs as:

> *A fit-for-purpose digital representation of an Observable Manufacturing Element (OME) with synchronization between the OME and its digital representation* [7,8,9].

Digitalizing lean can allow lean practitioners to leverage recent advancements in the manufacturing domain, such as Internet of Things (IoT), intelligent sensing, machine learning, artificial intelligence, and cloud computing. Introducing lean DTs can facilitate adaptable continuous improvement, robust industrial symbiotic relationships, increased worker buy-in, and seamless lean system integration in a CE.

This paper introduces a lean DT framework derived from current DT literature and standardization efforts. Here we explore the functional requirements needed to adapt an existing DT framework found in literature and the newly published ISO Manufacturing DT standard toward lean applications. First, we introduce and connect the two DT frameworks. Upon hybridizing the DT frameworks, we introduce the lean requirements and considerations per layer of the framework. The results of this work introduce a preliminary lean DT framework and highlight special considerations for adapting current DT frameworks toward applying lean principles. The latter can be useful for ongoing ISO 23247 manufacturing DT framework standardization efforts. Overall, this work provides a foundation for modernizing and digitalizing lean applications by introducing a lean-focused DT, explicitly focusing on facilitating the transition to a CE.

2 BACKGROUND

In this section we provide context to the lean DT requirements by defining the Circular Economy model and DTs. Furthermore, we present literature describing the connections between lean manufacturing, sustainability, and the CE. The section is closed with two manufacturing DT frameworks, one from Lappeenranta University of Technology (LUT) and one from the International Standards Organization, from which a lean DT framework is derived and function requirements are described.

2.1 The Circular Economy & Lean Manufacturing

Manufacturing industry is necessary to support economic prosperity and quality of life, but the current status quo of extracting, producing, and disposing of materials (i.e., the linear economy) is unsustainable [10]. Manufacturing directly accounted for an estimated 33 percent of direct US greenhouse gas emissions in 2019 (23 percent “Industry” and 10 percent “Agriculture”), not including impacts from manufacturing supply chains [11]. US industries generated an estimated 244-264 million metric tons of non-hazardous industrial waste in 2015, roughly equivalent to the 262 million tons of municipal solid waste generated that year [12,13]. Manufacturers and their stakeholders have been pushing to transition to less wasteful, more resource and energy-efficient operations across their supply chains [14]. This study addresses two fundamental models that are getting increasing attention for facilitating this transition: lean principles and the circular economy.

The circular economy model is becoming increasingly popular for manufacturers setting sustainability goals. A circular economy aims to eliminate waste by indefinitely cycling resources throughout the economy [15]. In a circular economy, materials are designed to be either kept in the economy indefinitely (a “closed loop system”) [3,16,17,18] or last longer before having to be landfilled or incinerated [19,20]. Retaining resource value solves many challenges, from resource scarcity [21,22] to environmental damage [23].

Several researchers have proposed combining lean and sustainability efforts but lack a proper framework for integrating the two and need more quantitative studies that provide benchmark data across a broad spectrum of stakeholders [17, 24, 25, 26]. Implementing lean and sustainable practices simultaneously requires immense planning and management [27]. Some researchers are not convinced that lean and sustainability principles are compatible, as some of their objectives contradict one another [25]. However, considering the ubiquity of lean practices in manufacturing and the pressures to integrate sustainability techniques like circular economy, a framework integrating the CE and lean systems provides a basis on which to move the work forward [28]. Circular economy principles can support green lean practices. Here lean, the reduction of waste to improve productivity, is different than green manufacturing where the focus is on improving sustainability of product systems by considering the 3Rs - Reduce, Reuse and Recycle. For example, Kurdve and Bellgran coalesced these two concepts by demonstrating that the waste hierarchy (a green manufacturing tool) is a valuable mechanism for implementing a circular economy into an otherwise lean system [29].

In their review of lean green manufacturing, Abualfaraa et al., suggest that lean and green can be synergistic, working in parallel to achieve either independent or shared goals [25]. In addition, Schmitt et al., suggest that lean green and the circular economy intersect at two points [24]. First, waste—a circular model sees waste as a resource that should be capitalized on, while a lean green model aims to eliminate waste [24, 30]. While their philosophies around waste differs, both concepts see waste at the end of a process as a failure to be addressed. The second place the concepts intersect is optimization. A circular economy focuses on stock optimization or maximizing the value of resources, while lean focuses on throughput optimization or getting products out quickly. However, stock and throughput optimization do not necessarily contradict, meaning that lean systems and the circular economy could work in parallel [24].

2.2 Digital Twin

A manufacturing DT is a virtual model of a physical element [7, 8]. Grieves introduced the concept of DTs in 2003. His definition ties a physical element to a digital counterpart [31]. Recently, DTs have gained much traction within industry and considerable attention from academia to understand how DTs can improve current processes [32]. To standardize DT implementation, ISO 23247 was created to define the terms associated with DT and provide use cases to ease implementation.

DTs are foundational to the current development of smart manufacturing systems. Real occurrences in the physical world can be anticipated and optimized by simulation in the cyber realm before being put into practice. With the rise of Industry 4.0, the use of the DT has increased with growing data availability. DT provides deeper insights into system status, making it easier for operation managers to comprehend their systems and adjust resources. [33].

2.2.1 Previous Research on Digital Twin Framework

Frameworks to apply DTs have been suggested through research and standards. This paper builds on two DT frameworks: Bazaz et al. and ISO’s 23257 Manufacturing DT Framework [34, 7, 8]. The framework introduced by Bazaz et al. suggests five layers (Cyber-Physical, Primary Processing, Models and algorithms, analysis, and Interface Layers) for applying DT within a manufacturing system [34]. ISO’s 23247 architecture is broken down into domains and entities: domains (Observational Manufacturing, Data collection, and device control, Core, and User) and entities (Observational Manufacturing, Data collection and device control, Core, User, and Cross-System entities).

2.3 Lappeenranta-Lahti University of Technology (LUT) Digital Twin Framework [34]

Bazaz et al. suggested a DT approach for manufacturing and production processes. The model combines a 5-Dimensional definition for the DT and cloud-based CPS (C2PS-Cloud Cyber Physical Space) architecture. The model uses five layers to reproduce the actual object as a virtual entity and to gather and process data. The LUT DT framework allowed for the analysis of the virtual model for future development projection, decision-making, reconfiguration, what-if analysis, and comprehension of the impact of changes in the real-time process. The virtual models and physical assets within the DT are joined through the user interface layer.

The use of Lean production can be made more effective by using a DT in manufacturing, which results in time and money savings. Due to the inherent uncertainty in manufacturing processes, the DT methodology is more suitable than pure simulation for the optimization of both the primary process and its sub-processes. A precise DT model can increase safety, reduce costs, hasten the production of new goods and the introduction of new procedures, and produce results for global optimization. However, in reality, the DT concept faces challenges with data provision because modern manufacturing uses a variety of data in various formats with various owners. The following subsections summarize the different layers that Bazaz describes.

2.3.1 Physical Layer The physical layer is the representation of the physical assets. The physical layer falls outside the scope of the Bazaz model. However, this layer is crucial in understanding the results and implications of a DT applied to a manufacturing system. In a general production system, the physical elements represented in the cyber-physical layer include machines, workers, factory floor layouts, and finished products. Adapting to lean manufacturing requires functionality beyond the original considerations of manufacturing assets.

2.3.2 Cyber-physical Layer The Cyber-Physical layer comprises systems created by and relies on the seamless fusion of physical elements and computer algorithms. This layer is a foundation for creating a DT. The cyber-physical data storage layer includes historical data from the company's production systems and data gathered from the physical model. In this layer, raw physical data collection is done with no processing, and data is supplied to the next layer, where the data processing takes place.

2.3.3 Primary Processing Layer The primary processing layer facilitates data exchange and processing. The data from the physical sensors are transferred to a cloud-based server through Open Platform Communications Unified Architecture (OPC UA) or a similar platform. Cloud-based processed data can be more readily utilized in optimization methods and further analysis techniques in subsequent DT layers. In the context of LM, data management is a crucial part of applying data-rich lean tools.

2.3.4 Model and Algorithm Layer The fourth layer is the Model and Algorithms layer. This layer stores methods and models for computational exploration of the solution space derived from the product system's data. The model and algorithm layer can store Computer Aided Design (CAD), statistical, simulation, and mathematical models. CAD programs are used to build the graphic model of the machine, manufacturing line, and shop floor layouts. The mechanical, electrical, hydraulic, simulation and mathematical models are selected and stored based on the purpose of the manufacturing DT.

For an LMDT (Lean Manufacturing Digital Twin), this layer can be adapted to store techniques and tools for continuous improvement. Some examples of these tools and techniques that stem from lean manufacturing are the following: Value Stream Mapping (VSM), (*Sort, Set in Order, Shine, Standardize, and Sustain* (5S)), Six Sigma, Just In Time (JIT), Kaizen, Kanban, Plan Do Check Act (PDCA), Root Cause Analysis (RCA), and Total Productive Maintenance (TPM) [35, 36, 37, 22, 29, 38, 39, 40, 41].

2.3.5 Analysis Layer The fifth layer is the Analysis layer. In this layer, models and tools stored in the previous layer can be analyzed, enhanced, redesigned, or reconfigured using a variety of data mining, machine learning, and AI techniques. For example, machine learning methods like neural networks can be leveraged to make predictions based on stored DT data and results from simulation or mathematical models.

Through the analysis layer, novel rules, predictions, and constraints can be continuously applied to the models and algorithm layer as data becomes available to leverage in analysis techniques. In essence, this brings the models and algorithm layer online and can provide understanding to users about the solution space in which the physical manufacturing system may react to modeled stimuli and data.

2.3.6 Interface Layer The interface layer is where people (operators or other users) interact with the results from the analysis layer. The interaction layer focuses on presenting the results in easy-to-digest methods through visualizations such as graphs and 3D models.

The adaption of this layer to a Lean Manufacturing Digital Twin (LMDT) requires the development of a Graphic User Interface (GUI) that can display lean tools and their data in easy to understand and visual manner. Moreover, the interface layer connects the various lean tools that use the same data.

2.4 ISO 23247 [7, 8, 9]

The ISO 23247 standard - *DT framework for manufacturing* - introduces the framework, shown in figure 1, for applying DTs across manufacturing sectors. The framework identifies two main components to implementing DTs: Domains and Entities. Entities represent either people or automation systems (e.g. through applied artificial intelligence or AI) that perform specific actions or processes. Domains segment other operations by function. Domains that are common across all sectors are where those actions and entities operate. The common domains for all sectors are Observational manufacturing, Data Collection and Device Control, Core, and User domains. The observational manufacturing domain is the object or process under observation. Data collection and cleaning happens in the Data Collection and Device Control domain. The Core Domain is where all the computation and analysis occurs. The User domain is focused entirely on the users, which can be workers in the process or outside stakeholders within domains. The entities match the domains, except there is an extra type of entity: the cross-system entity. The cross-system entity uniquely operates across different domains.

2.5 Connection between LUT Digital Twin framework and ISO 23247

Both frameworks explore how to apply a DT and what is needed for a DT to be successful. The LUT framework and the ISO standard mirror crucial areas. The LUT framework is broken into layers, and the standard is broken into domains. Shown in table 1, both use different lenses to identify overlapping areas. The Physical and Cyber-Physical layers of the LUT model are effectively within ISO's OME domain. The processing layer is analogous to the data collection and device control domain from the standard. ISO's core domain envelops most of LUT's layers. Specifically, the analysis and model and algorithms layers are

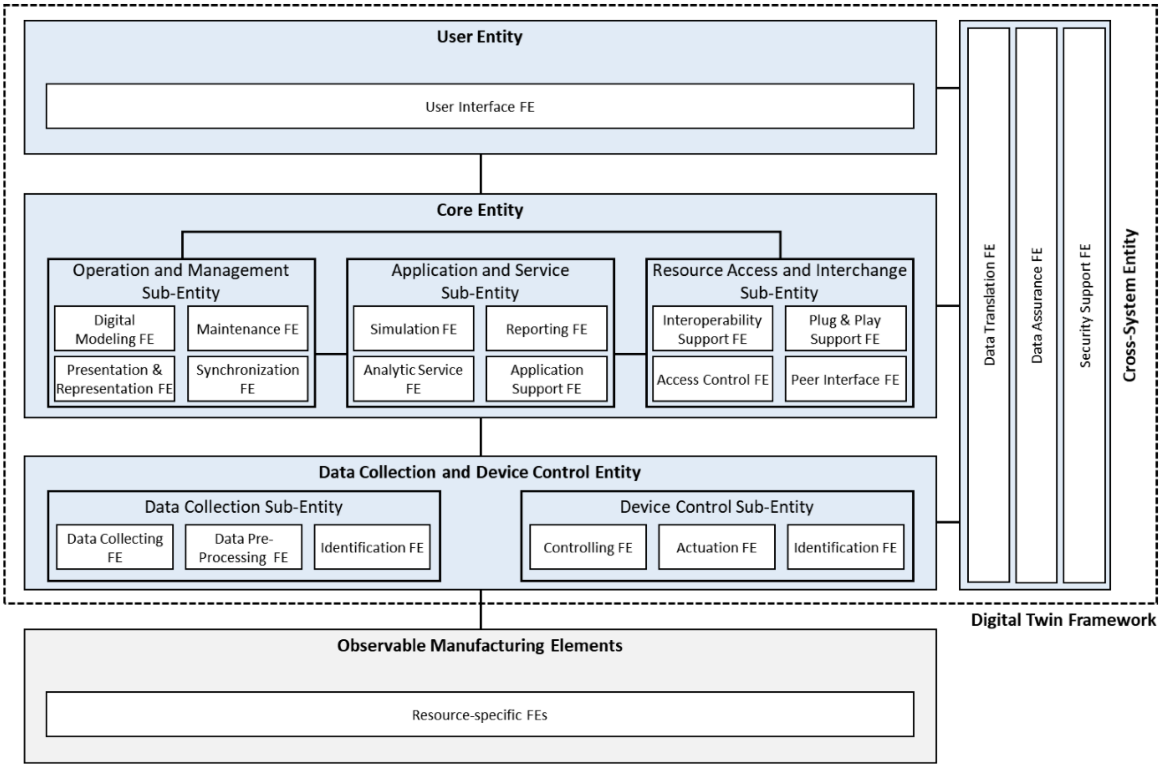

FIGURE 1. A FUNCTIONAL VIEW OF THE REFERENCE MODEL FOR ISO 23247 DT FRAMEWORK FOR MANUFACTURING [7, 8].

TABLE 1. MAPPING BETWEEN LUT & ISO 23247 DT FRAMEWORKS

ISO - Domain	*LUT DT - Layers*
Observational Manufacturing Element Domain	Physical Layer
	Cyber-Physical Layer
Core Domain	Primary Processing Layer
	Models and Algorithms Layer
	Analysis Layer
User Domain	Interface Layer

mapped to the core domain where the processing and analysis occur from the standard's point of view. The last ISO domain is the user domain communicated through the interface layer.

Both these frameworks are useful on their own, adding more detail to their respective scopes for DTs. The standard introduces the idea of entities, which helps consider human and cross-domain AI assets when applying the DT. The LUT framework expands on the “core” layer by breaking it down into multiple layers, effectively adding more depth to the framework.

A key component of lean manufacturing implementation is continuous improvement of current processes. While the standard does not explicitly state the framework's feedback nature, it encourages improvement within the DT framework through call and response across domains. However, for an LMDT, the feedback nature of the framework should be explicit.Focus on a feedback layer allows for human, external stimuli, and model collaborations that can best operationalize continuous improvement.

3 METHODOLOGY

This section explores the harmonization the two frameworks into one LMDT framework and subsequent lean requirements for an LMDT. The hybridisation of the two frameworks allow for concise identification of lean requirements needed to realize an LMDT in the context of both academic and standards-bases manufacturing DT approaches.

3.1 Lean Requirements for Digital Twins

Lean requirements for an LMDT system are the required functional needs for a DT system in order to apply lean. Functional requirements are traditionally defined as a requirement that describes an action a system must be able to perform or otherwise account for. Simply, a requirement that describes a system's input and output behavior [42]. In the context of lean, requirements are often defined as strategies to enhance efficiency, improve processes, decrease waste, and facilitate continuous improvement. Lean requirements of a DT framework can be expanded to include specialized consideration and handling of established lean tools and principles. While establishing the LMDT, we describe the lean requirements needed to facilitate a successful LMDT. Figure 2 shows the overview of the LMDT with lean requirements which hybridize the two DT frameworks.

3.2 Observational Manufacturing Element (OME) Domain

The OME Domain is shown at the top of the physicaland encompasses both the Physical Layer and the Cyber-Physical Layer from the LUT model.

3.2.1 Physical Layer Toward an LMDT, the number of physical assets increases to include items that behave on different temporal scales, are not directly attached to product systems, enter and exit the system periodically, and can include large assets outside the factory floor. Large assets can be suppliers and customers. In addition, many lean tools such as VSM, Poka-Yokes, and Kaizen are physical assets that are classically conventional and not in digital formats. Workers also interact with the LM systems more dynamically than in a non-lean manufacturing system. The lean tools mentioned previously, specifically Poka-Yokes and Kaizen, require worker buy-in to ensure continuous improvements and successful lean implementation. An LMDT will need the functionality to digitize lean tools, have a scalable scope, account for temporally dynamic assets, and facilitate a robust integration of workers as assets, observers, and stakeholders.

3.2.2 Cyber-physical Layer In lean manufacturing, value streams are frequently examined and redesigned using VSM, where process enhancement, waste minimization, and comprehensive product flow are examined. However, digitalization through Industry 4.0 is boosting the accessibility of industrial data. In literature, the focus on data preparation data utilization can enhance a VSM digitally. The LMDT can provide a database to systematically gather and compress this data in this respect and further data availability as more lean tools become digitalized.

Many of the requirements listed in the section 3.2.1 are similar to the functional requirements of the cyber-physical layer. In addition, there is an explicit requirement to enable the digitization of lean tools. As mentioned previously, VSM has been explored as a means to data-enrich lean processes through digital conversion. However, many lean methods rely on manual iteration, even in a digital format. The cyber-physical layer, and the entire OME domain by proxy, should explicitly address worker interface, section 3.4.1, including operators, data couriers, and the interface between the physical and cyber-physical space.

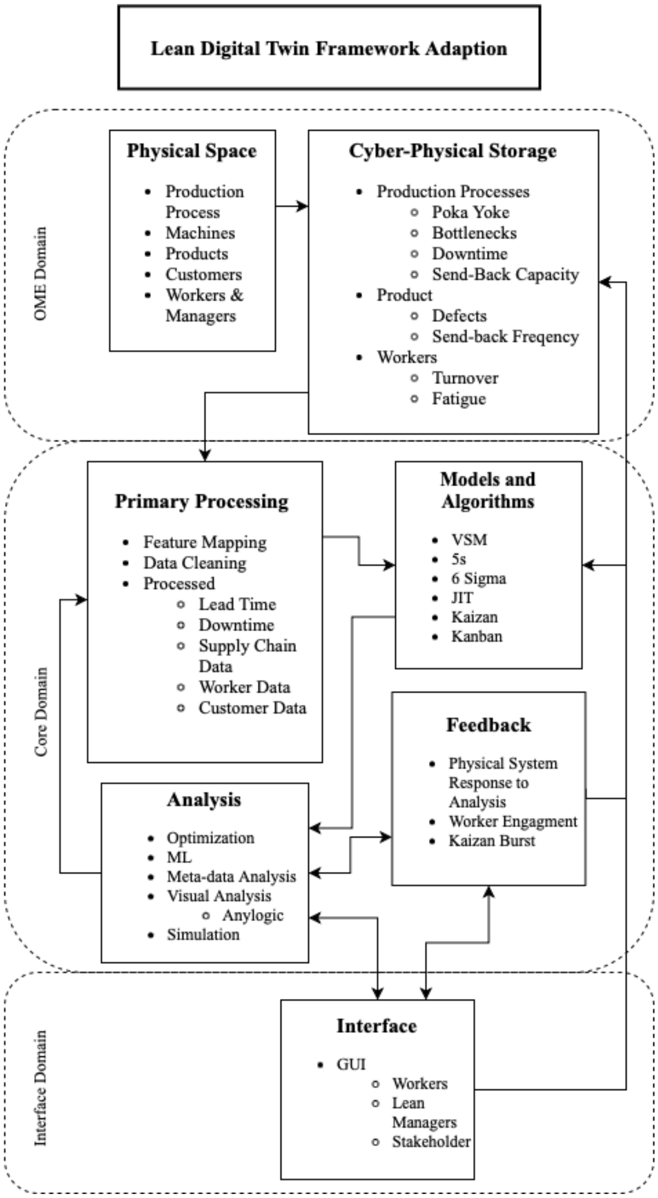

FIGURE 2. A LEAN MANUFACTURING DIGITAL TWIN. HERE DOMAINS AND LAYERS ARE COMBINED AND SHOWN WITH LEAN REQUIREMENTS.

3.3 Core Domain

While the Core Domain emphasizes computation and analysis, the LUT framework provides more detail of this function calling for the four areas described below applied to integrate lean functionality.

3.3.1 Primary Processing Layer Adapting this layer towards a more lean-focused framework requires the ability to reflect lean-focused data such as process, lead, changeover, and downtime. Lean manufacturing tools benefit from all the different types of data collected within and beyond the manufacturing system. Following the previous example, VSM leverages data that can come in parallel from many areas of the production system, supply chain, and stakeholder domains. An LMDT requires that all lean data be stored, updated, cleaned, and processed in a way that allows for multiple tools, layers, and domains to call the same data. Data features must be mapped and categorized based on the frequency and input method (workers, DT, or outside the lean manufacturing system). Furthermore, data can be modified in the analysis and algorithm layer through computation to curate generated data that should be stored and reprocessed separately from raw data inputs. An LMDT can benefit from robust data management systems such as HDF5, XML, and relational database management systems (RDBMS) [43, 44]

3.3.2 Models and Algorithms Layer For an LMDT, this layer can be adapted to store techniques and tools used to reach continuous improvement. Examples of these tools and techniques that stem from lean manufacturing are the following: VSM, 5S, six sigma, JIT, Kaizen, Kanban, PDCA, RCA, and TPM. For VSM, this layer would store a continuously updated VSM in a standard representation where data from previous layers is correctly connected and attributed within the VSM.

Toward lean functional requirements, lean tools and principles are often derivative of one another. The LMDT can include a few of these methods and principles during inception. However, the model and algorithm layer has a requirement to facilitate robust networking of input and outputs generated within and outside the layer as they relate to the lean tools. This can include integrated and derivative outputs from lean tools that have raw, predictive, or combined data inputs.

3.3.3 Analysis Layer In an LMDT, the analysis layer, in tandem with the model and algorithm layer, can provide the means for hybridizing classic lean tools and methods with modern analysis techniques. DT elements within the VSM can be improved through optimization and prediction methods that continuously improve the lean system. In addition, simulation tools like Anylogic can provide analytical insight into simulated changes modeled by lean tools and the physical lean system [45].

In the analysis layer, the LMDT requires that outputs from optimization, machine learning, visual analysis, and simulation be re-contextualized to lean tools through the models and algorithm layer prior to entering the feedback layer. Workers, lean managers, and stakeholders fluent in lean applications may need more expertise to interact and interpret raw results from the analysis layer. This layer is retained to enable the interpretation of generated data by experts who manage the machine learning, simulation, and mathematical programming methods. Furthermore, as lean becomes digitalized, lean practitioners will likely be familiar with the tools and methods within the analysis layer.

3.3.4 Feedback Layer The feedback layer is introduced in the manufacturing DT to facilitate human participation within many areas of the manufacturing DT system. The feedback layer formalizes the need for methods to operationalize changes and decisions recommended from the previous layers back to the physical system. For Lean, success is founded on continued communication between the human elements and the lean system. The feedback layer enables the communication between lean actors, the LMDT, and the physical LM system. The interface layer input from stakeholders, workers, and lean managers, along with previous DT layers, allow recommended improvements to be applied to the physical lean system.

3.4 User Domain

The User Domain details the interaction between humans and the other system operations and requires functionality for interacting with the users in ways that satisfy the objectives of lean principles while engaging the user's involvement. In addition, the User Domain can encapsulate the connection to external data sources that can impact the manufacturing system, as well as enable future circularity approaches. For example, future external data sources may contain information about availability or surge-based pricing for energy or materials to which the manufacturing system may adapt.

3.4.1 Interface Layer The adaption of this layer to an LMDT requires a human-friendly user interface that can display lean tools and their data in an easy-to-understand and visual manner. These may include traditional GUI or more sophisticated human-in-the-loop style interactions, e.g. applied gaming technologies, for instance for gathering operator input. Moreover, the interface layer needs to precisely establish the connections between various lean tools that use the same data. For example, in a VSM, each process can be expanded to give information on specific materials used, poka-yokes, the number of Kaizen bursts applied, or the frequency of defects related to the process. Furthermore, in relation to the analysis layer, predictions and optimization results related to a Kaizen burst can be overlayed on lean tools. Furthermore, seamless communication between the feedback and interface layers will need to be established. In the case of workers, they interact with both the interface layer and feedback layer to enact system changes. However, the interface layer facilitates quick transition and ease of access to different data types and assists in communication to lean managers and high-level stakeholders making decisions regarding the manufacturing process.

TABLE 2. LEAN REQUIREMENTS FOR A DIGITAL TWIN FRAMEWORK

Lean Requirements for a Digital Twin Framework		
Domain	*Layer*	*Requirements*
OME Domain	Physical Layer	- Operate on differing temporal scales
		- Account for workers as assets, stakeholders, and observers
		- Incorporate physically employed lean tools (VSM, Poka-Yoke, Kaizan Bursts)
	Cyber-Physical Layer	- Operationalize digitized lean tools
		- Explicit consideration of workers as lean operators, data couriers, and interface between the physical and cyber-physical layers
Core Domain	Primary Processing Layer	- Data must be processed in a way that can be called from multiple tools, domains, and layers simultaneously
		- Data must be categorized based on input method (workers, DT, or outside the lean system) and frequency
		- Data generated from thew models and algorithms layers should be reprocessed and stored separately
	Models and Algorithms Layer	- Facilitate robust networking of input and outputs of generated outputs from within and outside of the layer (lean tools and principles are often derivative from each other)
		- Handle integrated and derivative outputs from lean tools that have raw, predictive, or combined data inputs
	Analysis Layer	- Outputs from the Models and Algorithms layer needs to be re-contextualized to lean tools
	Feedback Layer	- Introduced to handle workers as assets, operators, lean practitioners, and observers
User Domain	Interface Layer	- Provide seamless communication between the Feedback and Interface layer
		- Facilitate quick and easy-to-access disseminate of results within the LMDT for stakeholders and lean managers
		- Engage in creative feedback methods such as gamification
		- Allow for connecting external data sets and other inputs related to the CE

4 RESULTS AND DISCUSSION

The results shown in table 2 represent functional requirements to realize an LMDT. The framework shown in figure 2 provides a guide for adapting existing DT frameworks to digital lean practices. As such, the mapping of LUT DTs and the ISO 23247 frameworks show that the frameworks can be congruent. The functional requirements for the standardization of lean within the DT space can be mostly met within the current standard framework. The work presented here offers an opportunity to expand on current academic research and the existing standard by adding lean-specific guidance. Furthermore, the LMDT framework provides opportunity to connect product life cycle areas advantageous to realizing a circular economy. Better, more efficient use of existing resources and integration with outward looking data related to broader material flows will be necessary to address the transition to more circularity of resources. Furthermore, future DT modeling practices will support better agility to respond to external stimuli.

Significant requirements for an LMDT involve unique considerations of workers within the DT. Lean practices are deeply invested in worker buy-in, activity, and action. The inclusion of the feedback layer is explicitly introduced to engage workers in a data-rich environment that allows them to provide operational feedback, explore solution spaces, and observe the DT of the lean manufacturing system. Future work should explore detailed integration of lean expertise from workers and lean managers to an operational LMDT.

The addition of a feedback layer is critical for adapting lean principles in the existing DT framework. For example, a VSM shows the entire sequence of processes, the flow of material, and areas where workers can provide input (called a Kaizen burst). DT lean tools should enable workers to view and communicate any changes to the process and quickly recommend solutions through Kaizen Bursts. In an LMDT, the feedback layer streamlines the process of measuring the impact of worker-submitted solutions through the connectivity of the analysis layer with the physical systems allowing the application of advantageous changes to be streamlined. In the LMDT framework, the feedback layer can be extended to address the need for increasing product lifecycle (PLC) area interoperability by providing and receiving real-time production information to supply chain and customer stakeholders.

5 CONCLUSION

In this paper, we introduce the functional requirements for adapting existing manufacturing DT frameworks toward lean systems. We introduce a three-domain and seven-layer DT framework following previous literature and standards. We describe the purpose of the layers and the layer-level functional requirements for lean adaption. To make this work more tractable in application, we explore lean adaptions to the ISO 23247 standard framework for manufacturing lean DTs. Furthermore, we explore the implications of lean and DTs being applied in a CE.

This paper emphasizes the role of the feedback layer in engaging the user in the operation of the physical system. A feedback layer allows stakeholders and workers to leverage analysis in the DT, ascertain the results of systemic changes, and aid in the decision-making process applied back to the physical system through the interface layer. In LMDTs, the feedback layer is paramount in continuous improvement and provides the ability to explore lean solutions digitally before physical application. A feedback layer allows stakeholders and workers to leverage analysis in the DT, ascertain the results of systemic changes, and aid in the decision-making process applied back to the physical system through the interface layer. In LMDTs, the feedback layer is paramount in continuous improvement and provides the ability to explore lean solutions digitally before physical application.

Future work may explore the application and use case of an LMDT. An LMDT implementation may solidify the validity and need for a feedback layer in manufacturing DTs. We intend to understand how to quantify LMDT application waste and explore how to optimize human-in-loop activities within a DT. In relation to a CE, we aim to explore how data from other PLC areas can be incorporated into an LMDT. Future work can explore the integration of other PLC domains such as design, use, supply chain, and end-of-life to support the lean objectives.

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