Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/WC02.20250045
Published: October 14, 2025

Performance Indicators and Digital Value Stream Mapping Implementation: An Industry 4.0 Application in SME

Angassu Girma Mullisa
College of Science Engineering and Technology
Faculty of Engineering
University of South Africa
Addis Ababa, Ethiopia
20619421@mylife.unisa.ac.za

Walid Abdul-Kader
Professor, Department of Mechanical, Automotive and Materials Engineering
Faculty of Engineering
University of Windsor
Windsor, Canada
kader@uwindsor.ca

Abstract

Manufacturing companies aspiring to adopt digitization in their production are increasingly required to make the best selection that would align with their sustainability goals. This research tackles a case study in a small and medium enterprise (SME) with the aim to assess the adoption of digital technology by mapping the relation between selected key performance indicators and the digitization technologies. The effects of the digitization technology regarding information flow in the value streams were studied while generating the digital value stream map. The study has mapped the effects of Industry 4.0 tools on selected KPIs to identify the most suited I4.0 tools for the SME considered. Accordingly, the projected production lead time in this SME has dropped from 654 hours (current state) to 290.16 hours (future state). The leanness score (another metric considered) has improved from 0.41 to 0.57. This research work can be helpful to decision makers who are planning to implement digitization into their production processes and hence proceed towards reaping the benefits of Industry 4.0.

Keywords
Digitization technology, Key performance indicators, Digital value stream mapping, leanness score.

1. Introduction
Present research works are increasingly investigating the compatibility of Lean manufacturing (LM) and Industry 4.0. The question of how to supplement traditional Lean manufacturing efforts with the emerging Industry 4.0 (I4.0) tools in a cost conscious manner is an ongoing area of study (Hines, 2023), (Teles, 2022), (Skalli, 2023), (Mayr, 2018). One aspect of Lean manufacturing among many that would benefit from the Internet of Things (IoT), Industry 4.0 tool and real-time data-driven process planning and simulation methods, would be the traditional value stream mapping (Lu, 2021) (Iyer, 2023) (Noto, 2021). Dynamic Value Stream Mapping (DVSM) is considered to supplement the traditional value streaming approach, which commonly provides a static description of the production behavior making quick responses impossible (Huang, 2022). The primary goal of value stream mapping (VSM) is to provide visualization of the process cycle times, inventory buffers, operational deployment, and information flow for a given process. However, there exists no stage that attempts to quantify and improve the management of process data and

information throughout the product value stream (Arey, 2021), (Meudt, 2017). Integrating digitization tools with the traditional VSM is one way to attain digital information flow. There are various approaches towards digitizing a manufacturing system. However, an approach that does not lead to large tie-up of resources is very much needed, especially by small and medium enterprises (SMEs) who are working to attain digitization in their production systems (Siedler L. A., 2020).

This research work is focused on assessing the all-important question of selecting applicable I4.0 tools to apply in SMEs by studying the effects of digitization on selected Key Performance Indicators (KPIs).

The remainder of this paper is structured as follows: section 2 presents a review of related literature, section 3 describes the research methodology, section 4 deals with the mapping of the KPIs and digitization technology and plotting the DVSM, section 5 evaluates the performance improvement achieved, and finally section 6 presents the discussion and conclusion.

1.1 Objectives

In this case study, an approach to selecting the best applicable digitization technology is made by mapping the effect of digitization technology on key performance indicators (KPIs). Once the applicable digital technology is selected, the effect of digital information flow and processing is assessed by plotting a digital value stream mapping. Finally, the projected performance improvement in the future state of the VSM is assessed by using a leanness score. Another novelty of this research work is careful attention to the cost projection for the adoption and implementation of digitization in a SME. This research work would be beneficial for manufacturing facilities and decision-makers who are interested in establishing digitization into their manufacturing systems and attaining digitized value streams in their processes.

2. Literature review

The objective of this case study is to attain performance improvement in a rebar manufacturing factory through mapping the (KPIs) and targeting implementation of digital technology. The research work further investigates the effect of digitization in information flow and processing through plotting the DVSM. The integration aspect of Lean manufacturing with the elements of Industry 4.0 is also investigated.

2.1 Adopting Lean Manufacturing in SMEs to Support Industry 4.0

According to Mofolasayo, the design principles of Industry 4.0 and Lean management tools reveal several opportunities for achieving synergies (Mofolasayo, 2022). The research work indicated a shortage of studies that promotes the integration of Industry 4.0 with Lean management. Potential improvements in Lean that can be achieved through the transmission of performance and operation data matrices using Cyber-physical systems (CPS) in real time are given as production surveillance, electronic Kanban, data analysis, total productive maintenance (TPM) and dynamic value stream mapping. Mrugalska has indicated linkage between Lean production and Industry 4.0 in the elements "smart product" whereby data collected allows for visualization of manufacturing processes and flow of information for the identification of waste. This closely relates with the Value stream mapping tool of Lean. "Smart machines" give better operational intelligence that helps avoid mistakes which is the main idea of Poka yoke Lean tool. "Augmented operator" using operator smart watches for real-time error messaging and error locating, links well with the failure notification and Andon methods which are the principal elements of Jidoka quality control methods (Mrugalska, 2017). Combination of automation technology with Lean production has been treated by (Satoglu, 2017) and (Kolberg, 2015) whereby automation-based Lean production applications are considered. A recommendation for a framework is provided by Kolberg. (Gomaa, 2025), has developed Lean 4.0 framework for the implementation of Lean principles with Industry 4.0. The study has outlined structured roadmap for Lean 4.0 adoption detailing key objectives, strategic actions and control mechanisms. (Rossi, 2022), treated mitigating Industry 4.0 problems related to inefficient digitization in organizations by implementation of Lean philosophy in the digitization environment. (Guimarães A., 2025) conducted empirical study on the impact of Lean Six Sigma and I4.0 on productivity of organizations by employing Exploratory Factor Analysis (EFA) and Structural Equation Modelling (SEM) techniques that displayed immediate impact of I4.0 on productivity and gradual effect of Lean Six Sigma tools over a period of time. Before Lean can solve digitization problems, its tools must be digitized in the context of Industry 4.0. VSM 4.0 is taken as a first pillar for supporting Lean operations due to its ability to monitor in real-time the flows of value in the enterprise. Kanban 4.0 is taken as the second pillar of Lean 4.0 implementation.

2.2 Digital Value stream mapping
According to (Arey, 2021), even though VSM is used to visualize the entire transformation of raw material to finished goods, there exists no stage that aims to formally quantify and thus, improve the management of data and process information throughout the product value stream. Meudt has suggested a holistic approach to information logistics as a means of improving traditional VSM through the identification and elimination of Information Logistic Waste (ILW). Digital improvement opportunities using "Swim lanes" have been used to represent distinct information flows including the relationship between information media, information connections and nature of data transported (Meudt, 2017), (Hartmann, 2018). (Arey, 2021) has enhanced the traditional VSM of a thermoplastics products manufacturing company by using KPC (key performance characteristics) at sources to realize improvement in the detection of detention time in the processes, which represents the longest possible period in which a KPC relevant defect may be produced and detected. Digital information flow has been accessed for improvement by analyzing the overall information transfer score. (Aziz, 2024) has explored performance improvement on the Overall Equipment Effectiveness (OEE) on a garment manufacturing facility through the coupled application of VSM 4.0 and DMADV (Define, Measure, Analyze, Design, Verify) methodology to attain a 14% increase on the OEE. (Kenedy, 2024), applied integrated DVSM and Cost time profile implemented through Integrated Dynamic Value Stream Mapping and Cost Time profile (INTACTS) to improve logistics aspect of an offshore drilling operation.

2.3 Mapping digital technologies with KPIs
Companies expect benefit from digitization in the form of cost and time saving. According to (Siedler L. A., 2020), small and medium enterprises (SMEs) need to focus on the targeted implementation of digital technologies to overcome budget restriction barriers. Mapping digital technologies with known KPIs to identify positive and negative impacts is taken as one selection method. Identification and analysis of KPIs using a hierarchical structure that categorizes them into supporting elements, basic KPIs and comprehensive KPIs are used to identify the relationship among KPIs towards measuring performance improvement (Kang, 2016). (Fairoos, 2020), has described the success of digital transformation in an organization as highly influenced by the effectiveness of the integration between key technologies with selected key success factors. (Meister, 2023), has applied KPIs to trace and quantify the effects of digitization tools in processing efficiency improvements by reducing Information Logistics Wastes (ILW).

Different researchers have proposed different architectures for the design and implementation of CPS. (Sony, 2020), has employed 8C architecture using the Lean Six Sigma (LSS) for the design of the CPS architecture. (Fitzgerald, 2015), has used collaborative model-based design of cyber physical systems that supports co-modeling, analysis, co-simulation, testing and implementation. (Shrivastava, 2016), discusses the design of CPS focusing on the correct interfacing of time through synchronizing clocks of computing systems to a high degree, enabling the building blocks of CPS to perform actions at a specified time.

In this case study, primarily, the use of KPIs as a means to selecting the most suited digital technology that fulfils the sustainability goals of the case company is considered. Then, the effect of digitization in the information flow of the value stream is assessed by plotting the DVSM. Finally, the performance improvement is projected using the Leanness score analysis. This research work would be useful for SMEs that are interested in implementing digital technology in their production systems towards attaining performance improvement.

The motivation behind using KPIs as a tool to select appropriate digital technology for the case company stems from the company's need to advance to Industry 4.0 and attain improved production efficiency. Numerous similar interests that are shared by many SMEs to advance using elements of digitization in their manufacturing units have inspired this research work. Though SMEs display an ardent interest in implementing I4.0, the budget restriction that they have mandates the careful selection of appropriate technologies and what aspect of their processes to digitize. The selection of digital technologies by assessing their effect on KPIs has not been considered in much research work. In this research work, the improvement of the VSM lean tool is considered by improving the information flow aspect of the value stream map. Applicable digitization technologies for this purpose are selected by mapping them with selected KPIs so that the sustainability goal of the case company is achieved.

3. Methods
The company addressed in this case study manufactures rebar of different diameters as its main product with an average yearly production capacity of 3,021 tons of rebar. The company also manufactures fencing and barbed wire to a lesser degree. An increasing competition from local and foreign suppliers has forced the company to develop

sustainability goals and proceed towards digitization. This research work focuses on selecting applicable KPIs to prioritize on dominant digital technology and hence, analyze the effects of digital information flow in the performance improvement of this rebar manufacturing plant. The research methodology consists of the following steps as is summarized in Figure 1.

a) Study the current value stream map of the case company. Data such as cycle times, work-in-progress between process steps, lead times and machinery uptimes are collected.
b) Applicable KPIs are selected that would assist to attain the sustainability goals of the company.
c) Suitable digital technologies to implement are identified through mapping the impact of the digital technologies on one or more KPIs by using technology mapping tools.
d) The future state dynamic value stream map is developed by integrating the improvement in the digital information flow.
e) The potential improvement in the operational performance of the case company through the application of digitized information flow is assessed by applying dynamic VSM.
f) Projected cost-benefit analysis is conducted.
g) Leanness improvement is projected and the significance of the research work for other SMEs is discussed.

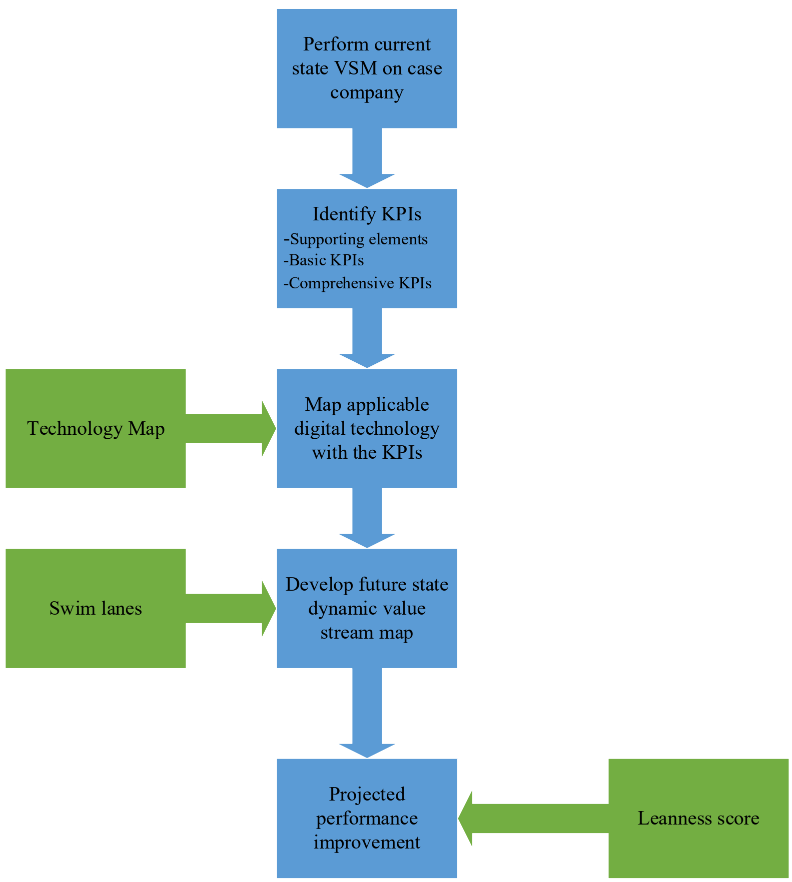

Figure 1. Research methodology

4. Data collection & analysis

4.1 Profile of the company under consideration

As indicated earlier, the research work is conducted in an Iron and steel factory that manufactures rebar for civil construction purposes in Ethiopia. The company manufactures different sizes of rebar following identical processing steps. The name of the company is withheld for confidentiality matters and referred to as ABC Company throughout the remainder of the paper. The research focused on determining a suitable digital technology and digital information flow for the ABC Company, and at the same time, projecting its effect on operational performance improvement on the ABC Company through the application of leanness analysis. The first step is mapping the current state VSM.

4.2 Traditional current state VSM

The rebar manufacturing step consists of feeding metallic scraps into induction furnaces. Upon reaching 1768 °C, the melt is ladled off to the continuous casting machine (CCM). The CCM is water cooled, and the formed billet is cut at suitable length, cooled, and stored. When required, the billets are fed into a re-heating furnace and passed on to the roughing process to change the rectangular billets into round ones. Then, through the rolling step, the billets pass through a series of dies to attain the required diameter of rebar. The formed rebars are passed to the air-cooling machines and passed to the cutting and packing station, respectively.

Primarily, plotting the traditional VSM of the ABC Company, seen in Figure 2, shows the Lean wastes of inventory in the form of work-in-progress and waiting time due to unbalanced processing lines. As described by (Arey, 2021), the traditional VSM illustrates inter-operational relationships and overall process visualization. The calculation of production lead time and its relative value-adding process times is also clearly seen. However, the traditional VSM does not treat, quantify, or improve the management of data and process information throughout the value stream.

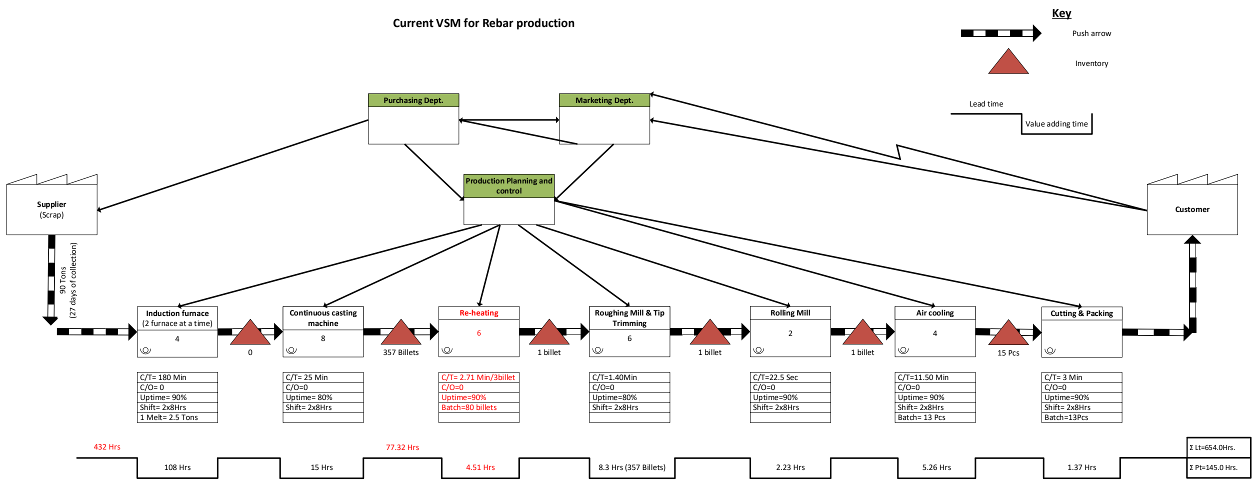

Figure 2. Current or traditional VSM of rebar production line

4.2 Mapping digital technology with KPIs

4.2.1 Defining KPIs

According to (Kang, 2016), supporting elements are data directly measured and collected during production operations. These are majorly categorized as time or quantity elements. The data collected of supporting elements is used to derive the basic KPIs that would describe a certain aspect of performance of a work unit. Applying the basic KPIs, the comprehensive KPIs are defined. Kibira, developed a simplified procedure for identifying and selecting KPIs for manufacturing as follows: establishing KPI objectives, KPI identification, selection, ranking and selecting the final KPI set (Kibira, 2018). Accordingly, from close consideration on the sustainability goal of the ABC Company with the stakeholders, prioritized sustainability goals have been selected as seen in Table 1. Then, the list of supporting elements, the basic KPIs and comprehensive KPIs have been considered as described in (Kang, 2016) and presented in Table 2.

Table 1. Prioritized sustainability goals for the company

Prioritized sustainability goals	Planned value
Total energy consumption	Reduce by 20%
Machinery downtimes	Reduce by 30%
Production lead times	Reduce by 25%
Throughput	Increase by 20%
Worker's efficiency	Increase by 40%

Table 2. Identified KPIs

Supporting elements category	**Supporting elements**	**Basic KPIs**	**Comprehensive KPIs**
Time elements	Actual unit processing time (APT)	Availability (A) $A = \frac{\text{APT}}{\text{PBT}} *100\%$	**Overall Equipment Effectiveness (OEE)** $\boldsymbol{OEE = A * E * QBR}$
	Planned busy time (PBT)		
	Actual personnel work time (APWT)	Worker efficiency (WE) $WE = \frac{APWT}{APAT} * 100\%$	
	Actual personnel attendance time (APAT)		
	Planned run time per item (PRI)	Effectiveness (E) $E = \frac{\text{PRI x PQ}}{\text{APT}} *100\%$	
	Produced quantity (PQ)		
Quantity elements	Good quantity (GQ)	Quality buy rate (QBR) $QBR = \frac{\text{GQ+RQ}}{\text{PQ}} *100\%$	
	Rework quantity (RQ)		
	Processed quantity (PQ)	Throughput rate (TR) $TR = \frac{\text{GQ+RQ}}{\text{AOET}} *100\%$	
	Actual order execution time (AOET)		
Energy elements	Energy produced on site (EPOS)	Energy per parts (EP) $EP = \frac{\text{EPOS} + \text{EOEG}}{\text{PQ}}$	**Energy efficiency (EE)** $\boldsymbol{EE = \frac{UE}{EC} *100\%}$
	Produced quantity (PQ)		
	Energy obtained from external grid (EOEG)	Energy consumed (EC) $EPOS + \text{EOEG} = \text{EC}$	
	Theoretical energy consumption per part (TECP)	Useful energy (UE) $UE = TECP * PQ$	
Maintenance elements	Time to failure (TTF)	Mean time to failure (MTTF)	
	Time to repair (TTR)	Mean time to repair (MTTR)	
	Corrective maintenance time (CMT)	Corrective maintenance ratio (CMR) $CMR = \frac{\text{CMT}}{\text{PMT}} *100\%$	
	Preventive maintenance time (PMT)		

4.2.2. Selecting applicable digital technologies

The selection of the most suited digital technologies for the ABC Company is performed following the technology map plotting method given by Siedler, by focusing mainly on the technology trends that prioritize predictive maintenance and integration of sensor networks for the ABC Company (Siedler S. Z., 2019). Applicable technologies for metal industries are adopted as described by (Branca, 2020) paying attention to applicable technologies suited for the ABC Company. Consideration of the type of applicable digital technology, potential use, and its effect on supporting elements is presented in Table 3 and Table 4 basing (Siedler L. A., 2020) to map the digital technology with selected KPIs. Primarily, the relation between the processing steps and supporting elements is plotted in Table 3, which is then projected in Table 4 to identify the most dominant digital technology.

Table 3. Process steps related to KPIs

Process steps	APT	APWT	PQ	GQ	RQ	AOET	EOEG	TTF	TTR	CMT	PMT
Induction furnace	+ (Process Control)	+ (process control)	–	–	–	–	+ (Data collection)	+ (Availability)	+ (Availability)	+ (Work instruction)	+ (Fault diagnosis)
Continuous Casting	+ (Process Control)	–	–	–	–	–	+ (Data collection)	+ (Availability)	+ (Availability)	+ (Work instruction)	+ (Fault diagnosis)
Roughing & tip trimming	+ (Process control)	+ (Process control)	+ (Quality control)	+ (Quality control)	+ (Quality control)	–	+ (Data collection)	+ (Availability)	+ (Availability)	+ (Work instruction)	+ (Fault diagnosis)
Rolling Mill	+ (Process Control)	–	–	–	–	–	+ (Data collection)	+ (Availability)	+ (Availability)	+ (Work instruction)	+ (Fault diagnosis)
Air cooling	+ (Process Control)	–	–	–	–	–	+ (Data collection)	+ (Availability)	+ (Availability)	+ (Work instruction)	+ (Fault diagnosis)
Cutting & packing	+ (Process control)	+ (Process control)	+ (Quality control)	+ (Quality control)	+ (Quality control)	+ (Process control)	+ (Data collection)	+ (Availability)	+ (Availability)	+ (Work instruction)	+ (Fault diagnosis)
Summary	**6**	**3**	**2**	**2**	**2**	**1**	**6**	**6**	**6**	**6**	**6**

Note: + = applied in the process step, – = Not applied in the process step

Table 4. Digital technologies mapped to supporting elements

Digital technology	Methods	Purposes	APT	APWT	PQ	GQ	RQ	AOET	EOEG	TTF	TTR	CMT	PMT
IoT	Automatic data collection	Acquiring data to control the system							6				
	Process control	Reducing waste by collecting manufacturing time	6	3									
	Quality control	Identifying and reducing defective parts			2	2	2						
	Increase availability									6	6		
Predictive maintenance	Fault diagnosis	Reducing downtime by detecting faults						1					6
	Work instruction in maintenance	Reducing time by displaying instructions at the machine										6	
Production line simulation	Manufacturing setup planning	Optimizing the manufacturing line											

Considering Table 3 and Table 4 simultaneously, they indicate primarily which KPIs are used in the successive processing steps. Secondarily, the relation between digital technology and the KPIs is mapped and the frequency of their dominance used to decide on the most applicable digital technology and KPIs to finally apply in the ABC Company. The following considerations are made for selecting the applicable KPIs in the processing steps in Table 3:

- The over processing step of Re-heating is considered as waste and continuous feeding of billets from the CCM to the roughing machine is taken as a primary improvement.
- In the process steps, continuous casting, rolling mill and air cooling, are automated process steps and the work pieces advance continuously from one step to another in the process. Hence, the quality control elements are not applied in these stations.
- In the induction furnace step, since the melted metal is poured into continuous casting mold, the quality control elements are not applied as there are no individual work pieces at the melting stage.

Hence the applicable I4.0 tools that are recommended by the technology mapping step with the applicable KPIs are indicated in Table-5 below.

Table 5. Applicable I4.0 tools for successive process steps

Processing step	KPI	I4.0 tool	Corresponding equipment	Applications
Induction furnace	APT	**IOT**	Digital timers synchronized with loading & unloading	DVSM control
	EOEG	**IOT**	Current & power consumption readers	High reading alerts
	TTF, TTR	**IOT**	Infrared pyrometers for sensing temperature	Sense surface refractory temperature and project time to failure
	CMT	**Cloud**	Cloud storage	Saving data collected from sensors
	PMT	**Big data analysis**	Phyton, SQL, Apache Hadloop	Perform projections on Trends and give feedback
		Virtual Reality	Interactive displays	Assist maintenance through training, supply information
Continuous Casting Machine	APT	**IOT**	Digital timers synchronized with optical sensors to identify loading & unloading	DVSM control
	EOEG	**IOT**	Current & power consumption readers	High reading alerts
	TTF	**IOT**	Infrared pyrometers & accelerometers for sensing vibrations	Read temperature and vibration levels
	TTR	**Cloud**	Cloud storage	Saving data collected from sensors
	CMT	**Big data analysis**	Phyton, SQL, Apache Hadloop	Perform projections on Trends and give feedback
	PMT	**Virtual Reality**	Interactive displays	Assist maintenance through training, supply information
• Roughing • Rolling • Air cooling • Cutting & packaging	APT, EOEG	**IOT**	Proximity sensors (for automatic starting of roller conveyors), accelerometers for sensing vibrations (bearings, gearboxes)	Read proximity sensing time and vibration levels
	TTF, TTR	**Cloud**	Cloud storage Phyton, SQL, Apache Hadloop	Saving data collected from sensors

	CMT	**Big data analysis**	Interactive displays	Perform projections on Trends and give feedback
	PMT	**Virtual Reality**		Assist maintenance through training, supply information

4.2.3 Digital value stream map

DVSM, which mainly focuses on the flow of information in the value stream, categorizes the modes of communication as verbal, paper based, electronic, semi-automatic and automatic. The information flow and relationship between the information media is shown in the future state value stream map using swim lanes map. The selected KPIs are shown in the future state map, see Figure 3 below. In the future state digital map, the over processing step of reheating has been completely eliminated by considering adjustment to the speed of the continuous casting machine and introducing fast conveyors for transporting the cast hot billets directly to the roughing machine to avoid the unnecessary cooling of hot billets and corresponding heat dissipation as described by (Bedarkar, 2014). This improvement would also remove the buildup of WIP between the processing steps of continuous casting and roughing operations. In the digitization of the ABC company, proximity sensors and automatic timers are integrated to collect actual unit processing times (APT) at the process steps.

Predictive maintenance is considered through the application of Vibration sensors at the processing steps so that the reading at different times is used to generate trends to predict failure times. Infrared sensors are used to analyze the temperature of the induction furnaces and CCM to assess the refractory condition and water-cooling jackets to perform predictive maintenance. Interactive digital displays at the production machines assist with the failure diagnoses of the machines, and record uptime and downtime data to improve on the overall equipment effectiveness, OEE. Electric power consumption meters are used at the machines to record energy usage and potential power consumptions from mechanical defects. Information is collected from the processing steps following primarily the ideas recommended on the upgrading of Legacy machines to CPS through retrofitting techniques using sensors and data transmission through wireless interface using Zig-Bee protocol to cloud infrastructure and applications to record and allow real-time monitoring (Fan, 2018), (Lima, 2019), (Huang, 2022), (Kutscher, 2020), (Kolla, 2022). Regular process data and alerts on control limits are sent to desk controllers to instruct corrections for individual process stations. The retrofitting consideration aspect for the digitization of the legacy machines is not within the scope of this paper. The improved digital VSM is shown in Figure 3 indicating the information flows within the future state arrangement.

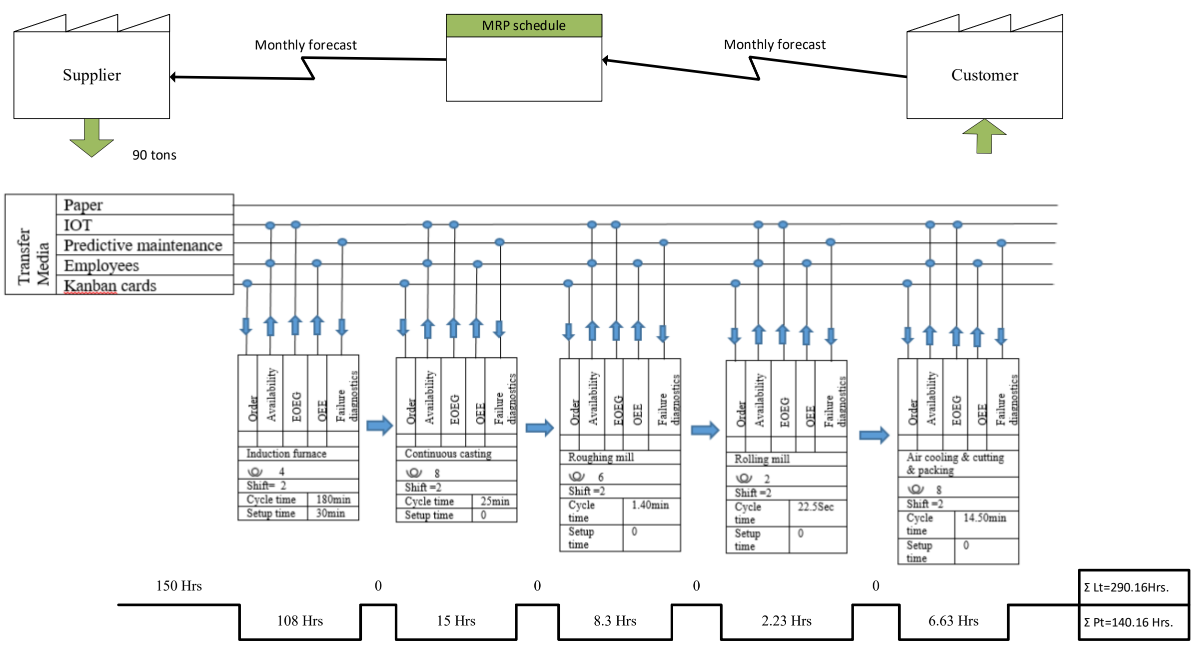

Figure 3. Digital value stream map using swim lanes

4.2.4 Cost-benefit analysis

In this section the cost benefit analysis which compares the cost of the project to the benefit in monetary terms is considered. The Net Present Value (NPV) analysis method is followed as given in Equation 1.

$NPV = \Sigma\ Present\ value\ of\ future\ benefits - \Sigma\ Present\ value\ of\ furure\ costs$ (Equation 1)

Considering a discount rate (r) of 6% and considering future benefits for 4 years from the time of implementation, the values for future benefits and future costs are given in Table 6 below.

Table 6. NPV analysis

Year	Cash inflow/outflow (Br.)	PV factor $(\mathbf{1/(1+r)^n})$	Amount (Br.)
0	-750,000.00	1.0000	-750,000.00
1	150,000.00	0.9434	141,510.00
2	280,000.00	0.8900	249,200.00
3	500,000.00	0.8396	419,800.00
4	580,000.00	0.7921	459,414.00

Note: Br = Birr is the local currency of Ethiopia, 135 Birr = 1USD.

NPV = 519,924.00 Br.

Since the NPV value is positive the project is taken as viable.

5. Results and Discussion

In this case study, the primary motivation for integrating digital information flow to the traditional VSM is the improvement of the operational performance of the ABC company through the reduction of total internal lead time. An additional performance analysis, the leanness score is calculated to account for the effects of the integration of digital information flow into the value stream. Value-added and non-value-added activities are identified to quantify the level of leanness. The leanness measure has been used by (Huang, 2022) and (Wan, 2007) to provide an objective and quantitative evaluation of the process performance. The simplified mathematical expression for leanness is given below in Equation 2.

$$Leanness = \frac{1-\left(\frac{1}{2}\right)\left(\frac{(Xta-Xti)}{Xta}+\frac{Xca-Xci}{Xca}\right)}{1+\left(\frac{1}{1}\right)\left(\frac{Xvi-Xva}{Xva}\right)} \quad \text{(Equation 2)}$$

The Actual Decision-Making Unit, ADMU is based on (X_{ta}, X_{ca}, X_{va}), and the Ideal Decision-Making-Unit, IDMU is based on (X_{ti}, X_{ci}, X_{vi}).

X_{ta} = production lead time from VSM

$X_{ca} = \frac{Daily\ cost\ of\ production}{Daily\ amount\ of\ delivered\ products}$

$X_{va} = Retail\ price * Customer\ satisfaction$

X_{ti} = Processing time from VSM

$X_{ci} = \sum\left(\frac{Daily\ VA\ cost\ of\ a\ VA\ process}{Delivered\ amoun*(1+Scrap\ rate)}\right.$

$X_{vi} = Retail\ price * Customer\ satisfaction$

An actual DMU (ADMU) is an observation of the actual production with actual time and cost as the input variables while the created value is output variable. In contrast, an ideal lean DMU (IDMU) only includes the value added (VA) costs and (VA) times (Huang, 2022). Inserting the values of the variables for both current state and future state into Equation 2, gives the value of the variables as presented in Table 7.

Table 7. Leanness score analysis

	Xta	Xca	Xva	Xti	Xci	Xvi
Current state	654.0 Hrs.	$\frac{569{,}600\ Br}{10{,}000 Kgs}$ = 56.9Br/Kgs	113.92Br/Kg *75% = 85.44	145.0Hrs.	33.20 Br/Kg	85.44 Br/Kg
Future state	290.16 Hrs.	$\frac{344{,}760\ Br}{10{,}000 Kgs}$ = 34.1Br/Kgs	113.92Br/Kg *95% = 108.22	140.16 Hrs.	22.51 Br/kg	108.22 Br/Kg

Current state leanness score= **0.41**
Future state leanness score= **0.57**
Hence, the result shows that the production lead time is projected to decrease from 654.0 hours in the current state (see Figure 2) to 290.16 hours in the future state (see Figure 3). The leanness score has also improved after the adoption of digital technology from a score of 0.41 (current state) to a score of 0.57 (future state).

6. Conclusion

Manufacturing companies are increasingly pushed by the global market situation to improve their processing efficiencies through the adoption of digital technologies to advance to Industry 4.0. The integration of lean production with Industry 4.0 elements such as IoT is gaining favor in manufacturing industries. Hence, the question of adopting the most suitable digital technologies and the improvement achieved by the value stream is a major point of interest. Thus, in this research work, applicable KPIs are defined and the potential relationship of the KPIs with the selected digital technology is mapped. Then, the effect of digitization on the information flow and value flow is assessed by plotting the digital VSM. Finally, a qualitative evaluation of the process performance is assessed through the leanness score and observing the improvement on total lead time. This research work is useful for companies that are interested in adopting digitization in their production systems and take full benefit from the integrated application of lean production with digitization technologies and improved information flow.

6.1 Future research interests

Effective, cost-conscious digitization of small and medium enterprises is an area of great interest in the effort towards advancing to Industry4.0. The following future research interests are suggested to strengthen the effort.

- Implementing suitable digitization technology is a very important consideration especially for SMEs as they work with restricted budget. More analysis tools to mapping and identify optimum digital technology are recommended as a future research area.
- The application of KPIs as a performance indicator tool is well established but more research is recommended for using KPIs as a means of identifying suitable digital technologies and dictating the digitization and digital information flow within a value stream.
- DVSM is a very useful tool to analyze and improve the digital information flow in a value stream. More research studies on the integrated application of simulation tool and IoT towards plotting the instantaneous, real-time digital value stream and an automated checking of the KPIs to send feedback through digital twin application are recommended.

Reference

Arey, L. G., *Lean Industry 4.0: A digital value stream approach to process improvement*, *Procedia Manufacturing*, 10th CIRP Conference on Digital Enterprise Technologies (DET 2021) – Digital Technologies as Enablers of Industrial Competitiveness and Sustainability, pp. 19–24, Chatham, United Kingdom, 2021, Elsevier.

Aziz, T. B., *Improving equipment effectiveness through visual stream mapping: Some exploratory research findings in the ready-made garment (RMG) sector*, *Global Journal of Flexible Systems Management*, pp. 303–324, 2024, doi: https://doi.org/10.1007/s40171-024-00386-z.

Bedarkar, S., *Energy saving by direct rolling of hot billets through high speed casters*, *Electrotherm Group Ltd.*, India, 2014.

Branca, F. C., *The challenges of digitization in the steel sector*, *Metals*, MDPI, 2020, doi: https://doi.org/10.3390/met10020288.

Fairoos, N. W., *A review on improving performance through digital transformation: A study of best technologies and key success factors*, *Proceedings of the 2nd African International Conference on Industrial Engineering and Operations Management*, pp. 1124–1133, Harare, Zimbabwe, 2020, IEOM Society International.

Fan, C., *Embedded smart box for legacy machines to approach Industry 4.0 in smart manufacturing*, *MATEC Web of Conferences*, vol. 185, p. 00027, 2018, doi: https://doi.org/10.1051/matecconf/201818500027.

Fitzgerald, G. L., *Cyber-physical systems design: Formal foundations, methods and integrated tool chains*, *IEEE/ACM 3rd FME Workshop on Formal Methods in Software Engineering*, pp. 40–46, Newcastle upon Tyne, UK, 2015.

Gomaa, A., *Lean 4.0: A strategic roadmap for operational excellence and innovation in smart manufacturing*, *International Journal of Emerging Science and Engineering (IJESE)*, vol. 13, no. 5, pp. 1–20, 2025, doi: https://doi.org/10.35940/ijese.D2592.13050425.

Guimarães, A. O. E., *Effects of Lean tools and Industry 4.0 technology on productivity: An empirical study*, *Journal of Industrial Information Integration*, pp. 1–10, 2025, doi: https://doi.org/10.1016/j.jii.2025.100787.

Hartmann, M. S., *Value stream method 4.0: Holistic method to analyse and design value streams in the digital age*, *Procedia CIRP*, vol. 78, pp. 249–254, 2018.

Hines, T. A., *Lean Industry 4.0: Past, present and future*, *Quality Management Journal*, vol. 30, no. 1, pp. 64–88, 2023, doi: https://doi.org/10.1080/10686967.2022.2144786.

Huang, J. K.-M., *The implementation of Industry 4.0 in manufacturing: From Lean manufacturing to product design*, *International Journal of Advanced Manufacturing Technology*, vol. 121, pp. 3351–3367, 2022.

Iyer, S. D., *Digitization: A tool for the successful long-term adoption of Lean manufacturing*, *Procedia CIRP*, 30th CIRP Life Cycle Engineering Conference, pp. 245–250, Pilani, India, 2023.

Kang, Z. L., *A hierarchical structure of key performance indicators for operation management and continuous improvement in production systems*, *International Journal of Production Research*, vol. 54, no. 21, pp. 6333–6350, 2016, doi: https://doi.org/10.1080/00207543.2015.1136082.

Kenedy, W., *The integration of dynamic value stream mapping and cost-time profile method for optimizing offshore logistics base operations*, *Indonesian Journal of Multidisciplinary Science*, vol. 3, no. 10, pp. 1–6, 2024.

Kibira, B. F., *Procedure for selecting key performance indicators for sustainable manufacturing*, *Journal of Manufacturing Science and Engineering*, vol. 140, p. 011005, 2018.

Kolberg, Z., *Lean automation enabled by Industry 4.0 technologies*, *IFAC-PapersOnLine*, pp. 1870–1875, 2015.

Kolla, L. K., *Retrofitting of legacy machines in the context of Industrial Internet of Things (IIoT)*, *Procedia Computer Science*, 3rd International Conference on Industry 4.0 and Smart Manufacturing, pp. 62–70, Luxembourg, 2022, doi: https://doi.org/10.1016/j.procs.2022.01.205.

Kutscher, O. A., *Upgrading of legacy systems to cyber-physical systems*, *Proceedings of TMCE*, pp. 1–12, Dublin, Ireland, 2020.

Lima, M. M., *IoT energy retrofit and the connection of legacy machines inside the Industry 4.0 concept*, *IEEE Proceedings*, pp. 5499–5504, 2019.

Lu, L. M., *A digital twin-enabled value stream mapping approach for production process reengineering in SMEs*, *International Journal of Computer Integrated Manufacturing*, vol. 34, nos. 7–8, pp. 764–782, 2021, doi: https://doi.org/10.1080/0951192x.2021.1872099.

Mayr, W. K., *Lean 4.0 – A conceptual conjunction of Lean management and Industry 4.0*, *Procedia CIRP*, 51st CIRP Conference on Manufacturing Systems, pp. 621–628, Nuremberg, Germany, 2018.

Meister, V. S., *Model-based framework for lean information logistics in digital production*, *Procedia CIRP*, 16th CIRP Conference on Intelligent Computation in Manufacturing Engineering, pp. 80–85, Augsburg, Germany, 2023, doi: https://doi.org/10.1016/j.procir.2023.06.015.

Meudt, M. A., *Value stream mapping 4.0: Holistic examination of value stream and information logistics in production*, *CIRP Annals – Manufacturing Technology*, vol. 66, pp. 413–416, 2017, doi: https://doi.org/10.1016/j.cirp.2017.04.005.

Mofolasayo, Y. M., *How to adapt Lean practices in SMEs to support Industry 4.0 in manufacturing*, *Procedia Computer Science*, 3rd International Conference on Industry 4.0 and Smart Manufacturing, pp. 934–943, Edmonton, Canada, 2022.

Mrugalska, W., *Towards Lean production in Industry 4.0*, *Procedia Engineering*, 7th International Conference on Engineering, Project, and Production Management, pp. 466–473, Poznan, Poland, 2017, doi: https://doi.org/10.1016/j.proeng.2017.03.135.

Noto, C., *Introducing a strategic perspective in Lean thinking applications through system dynamics modelling: The dynamic value stream map*, *Business Process Management Journal*, vol. 27, no. 1, pp. 306–327, 2021, doi: https://doi.org/10.1108/BPMJ-03-2020-0104.

Rossi, L. T., *Lean tools in the context of Industry 4.0: Literature review, implementation and trends*, *Sustainability*, vol. 14, p. 12295, 2022, doi: https://doi.org/10.3390/su141912295.

Satoglu, U. C., *Lean transformation integrated with Industry 4.0 implementation methodology*, pp. 1–10, Istanbul, 2017.

Shrivastava, B. D., *Time in cyber-physical systems*, *Proceedings of the Association for Computing Machinery*, Pittsburgh, USA, 2016, doi: https://doi.org/10.1145/2968456.2974012.

Siedler, L. A., *Modelling and assessing the effects of digital technologies on KPIs in manufacturing systems*, *Procedia CIRP*, 53rd CIRP Conference on Manufacturing Systems, pp. 682–687, Kaiserslautern, Germany, 2020.

Siedler, S. Z., *Categorizing and selecting digital technologies for their implementation within different product life cycle phases*, *Procedia CIRP*, Conference on Intelligent Computation in Manufacturing Engineering, pp. 274–279, Gulf of Naples, Italy, 2019.

Skalli, C. C.-R., *Industry 4.0 and Lean Six Sigma integration in manufacturing: A literature review and integrated framework and proposed research perspective*, *Quality Management Journal*, vol. 30, no. 1, pp. 16–40, 2023, doi: https://doi.org/10.1080/10686967.2022.2144784.

Sony, M., *Design of cyber-physical systems architecture for Industry 4.0 through Lean Six Sigma: Conceptual foundations and research issues*, *Production & Manufacturing Research*, pp. 158–181, 2020, doi: https://doi.org/10.1080/21693277.2020.1774814.

Teles, A. N., *The synergy of Lean manufacturing methodology in the context of Industry 4.0: An integrative review*, *Research, Society and Development*, vol. 11, no. 13, pp. 1–12, 2022, doi: https://doi.org/10.33448/rsd-v11i13.35449.

Wan, C. R., *Leanness score of value stream maps*, *Proceedings of the 2007 Industrial Engineering Research Conference*, pp. 1–7, San Antonio, USA, 2007.

Biographies

Angassu Girma Mullisa is a PhD student at the University of South Africa. He holds a master's in industrial engineering and bachelor's in mechanical engineering from the Addis Ababa Institute of Technology, Addis Ababa, Ethiopia. His research interest includes performance improvement of industries through integrated application of Lean and Industry 4.0 tools. His research focuses on the digitization of SMEs through development of frameworks.

Walid Abdul-Kader is a Professor of Industrial Engineering at the University of Windsor. He is also the Director of the Systems Optimization Research Laboratory in the Faculty of Engineering. His research works relate to performance evaluation of manufacturing / remanufacturing systems prone to random failure. Dr. Abdul-Kader received a bachelor's degree in industrial engineering from the University of Québec in Trois-Rivières, a master's degree in mechanical engineering from École Polytechnique de Montréal, and a PhD degree from Université Laval, Québec, Canada. His research works are published in various peer-reviewed journals in his field and cited by a worldwide audience of researchers.