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LEAN MANUFACTURING ENHANCED BY INDUSTRY 4.0

Analyzing the relationship and developing a conceptual, integrative model for the digital transformation

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ABSTRACT

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Name of thesis LEAN MANUFACTURING ENHANCED BY INDUSTRY 4.0. Analyzing the relationship and developing a conceptual, integrative model for the digital transformation.		
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Lean management system has been highly appreciated in the manufacturing industries for the past 50 years and is a mature and well-established topic for discussion. The main objective of a Lean Manufacturing is adding value for the customer, reduce waste in the overall value chain and create a culture of continuous improvement in the industry. Since 2011, when the term Industry 4.0 was introduced the Fourth Industrial Revolution has been considered as an opportunity for industrial business and industries are looking for ways to utilize all the advantages this transformation could bring.

The purpose of the study was to analyze the relationship between Lean Manufacturing, Industry 4.0 and develop an integration model that could address the concerns of organizations implementing Lean Manufacturing and Industry 4.0.

The thesis is completely based on theoretical research. The author describes the relationship among two different management paradigms and introduces a model based on philosophy, principles and pillars.

Key words
Continuous improvement, Industry 4.0, Lean Management, Manufacturing industries.

CONCEPT DEFINITIONS

AGV	Automated Guided Vehicle
AM	Additive Manufacturing
AR	Augmented Reality
BD	Big Data
CM	Cloud Manufacturing
CPPS	Cyber Physical Production Systems
CPS	Cyber Physical Systems
HMI	Human Machine Interface
IoT	Internet of Things
JIT	Just in Time
LM	Lean Manufacturing
LPS	Lean Production System
MaaS	Mobility as a Service
MFC	Material Flow Control
PaaS	Platform as a Service
RFID	Radio Frequency Identification
SMED	Single Minute Exchange of Die
SPC	Statistical Process Control
TPM	Total Productive Maintenance
VR	Virtual Reality
VSM	Value Stream Mapping

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1 INTRODUCTION

Lean is considered to be one of the most efficient manufacturing systems that have been adopted in manufacturing companies globally. Lean Manufacturing as a concept was developed in Japan in the early 1950's and it was created as a survival strategy to provide solution to the challenges that the Japanese industry was facing after the second world war. The basic idea was to produce more output by the use of less input in the process. The core concept of Lean is the reduction of waste in the production process that ultimately increases the efficiency which contributes in the reduction of production costs. Lean Manufacturing method aims at minimizing the manufacturing costs and maintaining high standards. The main objective of Lean Manufacturing is to synchronize humans with the manufacturing process that enables sustainability and the culture of continuous improvement of the whole process. (Singh 2017.)

The term Industry 4.0 was introduced in 2011 at the Hannover Messe in Germany. Industry 4.0 is the Fourth Industrial Revolution that is taking place already which is characterized by connectivity, collaboration, advanced services and manufacturing technologies. Industry 4.0 is focused on creating smart manufacturing environment within production system. Industry 4.0 is a futuristic vision of industry and manufacturing where information technologies are going to increase the efficiency and competitiveness by the interconnection of every resource within the value chain. The Fourth Industrial Revolution consists of two main components of smart manufacturing technologies which are Information technologies and operation technologies. (Malavasi& Schanetti 2017.)

Manufacturing industries are inevitably being hit by the great change brought by Industry 4.0 therefore, they are trying to fit Industry 4.0 with the pre-existing business philosophy. Almost 90% of the highest grossing manufacturing companies enjoy their status because of the successful implementation of Lean Manufacturing principles and methods within the organization and the fact emphasizes the reason why the interaction between Lean manufacturing and the concepts of Industry 4.0 is of utter importance. (Golchev 2019.)

The study aims to examine the relationship between Lean Manufacturing and Industry 4.0, and to develop an integrative model that could support both LM tools and I4.0 technologies. The report is divided into three parts. Firstly, a holistic review of Lean Manufacturing and Industry 4.0 will be presented where LM and I4.0 will be fragmented into Philosophy, Principles and Pillars. In the second part the relationship between LM and I4.0 will be examined which will be categorized into interdependencies, correlation and sustaining and disruptive changes. The existing models for integration will be reviewed in the second part as well. The third part will be dedicated to developing a model for integrating LM and I4.0 which will be based on philosophy, Principles and pillars integration.

2 LEAN MANUFACTURING

The term Lean first appeared in the article “Triumph of the Lean Production System” in 1988 by John F. Krafcik on his thesis at MIT Sloan School of Management. In his paper, he introduced the word to compare the Western production systems, which he defined buffered, with the innovative Toyota Production System, which was developed in Japan after WWII. In 1990, the book “The Machine that Changed the World” introduced the TPS to manufacturers in western society, which promoted Lean as an alternative to the traditional mass-production concept created by Ford (Pentlicki 2014). Lean was introduced in the 1950s by Ohno in Toyota; it is a set of different synchronized methods and principles used to control manufacturing sites. The process arises as a mean of organizing the production systems and its components in order to reach a shorter lead time with minimized cost and highest attainable quality (Singh 2017).

Different authors have defined Lean in diverse ways to illustrate their perception and illustrate their claims. The authors also seem to have various opinions on which characteristics are to be associated with Lean concepts. Lean can be defined as a process, a way, a set of principles, an approach, a theory, a set of tools and techniques, a practice, a philosophy, a system, a manufacturing paradigm, a model, or a program. (Bhamu & Sangwan 2014.)

Taiichi Ohno wanted to develop a means to overcome the economic crisis faced by the Japanese automotive industry after the WWII. He noticed that American car manufacturers were able to produce nine times as much as Toyota’s over the same amount of time as they manufactured large batch sizes to compensate the long-set up times and to reach economies of scale (Leyh, Martin & Schaffer 2017). Such large-scale manufacturing was not possible for Toyota since its production volume was too small. Thus, Toyota implemented measures to acquire a leaner production; hence, they developed a system that would “Do More With Less” which means using the lowest amount of resources to obtain the highest amount of efficiency and quality by focusing on waste elimination, continuous improvement, maximizing capacity, reduction of inventory, improved productivity and empowering of workers (Wilson 2015).

2.1 Lean Philosophy

Lean manufacturing has two primary purposes: customer satisfaction and profitability. Every action performed during the production must provide necessary value to the end customer, and that is the reason why it is crucial to understand the desire of the customer and the amount they are willing to pay for. An organization operating on Lean understands customer value and focuses its processes on continually increasing it by creating a perfect value creation process that has zero or minimum amount of waste. The main objective of Lean Manufacturing is to create a streamlined flow of processes to produce the product at the required pace of customer's demand and continually shorten the time between order and delivery by eliminating everything that increases time and cost (Shah & Ward 2003). Lean can also be defined as a journey of value-adding by declining the amount of wastes and defects; according to a Lean perspective, the best way to increase profitability is by reducing waste, which is directly associated with cost as much as possible (Malavasi & Schenetti 2017).

Waste is considered as a central term in classic lean literature. Waste creates unnecessary time loss and increases cost. All non-value adding activity or non-required movement on the work floor creates wastes. The Toyota Production System has defined three broader types of waste which are.

1. **Muda**: Muda refers to a waste of unnecessary activities. Original wastes create on the work floor connecting to a waste of money, time, and resources: inventory, physical motion of a worker, waiting, movements of products, overproduction, over-processing, and defects. The goal of identifying Muda is to recognize whether steps are required to the process or not and eliminating or reducing those unnecessary steps in the process. (Malavasi and Schenetti 2017; Pieńkowski 2014.)

2. **Muri**: Muri is associated with overburden or unreasonableness of overloading equipment, facility, or people resources beyond its capacity, which puts employees and machines into unnecessary stress, reducing their ability of performance. It can also be identified as the opposite of overburden- the underutilization of man and equipment that creates a lengthy period of idle time. (Pieńkowski 2014.)

3. **Mura**: Mura refers to variation or unevenness. It is a waste of unevenness in production volume that creates variation in production schedule and unevenness in production workload and pace of work. (Pieńkowski 2014.)

Lean Manufacturing has identified seven different types of waste in the production facility which are as follows.

Transportation- the waste of transportation occurs whenever goods or materials are moved around; it does not create value but is often indispensable. Some form of transportation will always be necessary, but the act of only moving things around the floor adds no real value to the product or service. It must be highlighted that the more a product is transported, the more likely it increases delays increasing cost, time or would increase the defects during motion and loss of quality. (Pereira 2009.)

Inventory- this form of Muda is referred to as raw materials, work in progress, or finished products that spread all over the production floor and warehouse. This form of waste is complex because, for producers of any types of goods or services, a certain amount of inventory is required so, it must be carefully controlled. The presence of a lower level of stock allows the guaranteeing of continuity of the production process if the manufacturing is discontinuous or characterized by a higher amount of product types. The storage period of products and components does not add any kind of value. It generates costs for lighting, handling, immobilization, air-conditioning, etc. and is always associated with risk of damage. (Kovacs 2012.)

Motion- is probably the most misunderstood waste as it is often confused with the waste of transportation. It is the waste of motion in any movement made by employees and moving of the equipment that does not add value to the product or service. It is a form considered to be an extremely productivity killer as it only increases the cost and increases the amount of time. (Simboli, Taddeo & Morgante 2014.)

Waiting-it occurs when the operators are stopped or are idle waiting for the parts, machines, or other workers. Anytime when the workers are queued up, this form of waste happens. It could occur when an operator or a machine is waiting for the right component, part, or information. Material waiting means the material is not flowing to the next step, which affects negatively the cost and time. (Dilanthi 2015.)

Overproduction- is also called the mother of all wastes, and it occurs when a company produces more than its customer (internal or external) needs. It is considered the mother of all wastes as the waste of overproduction gives birth to other forms of waste. Excess goods created need to be moved around and stored, creating a waste of inventory and waste, which requires people to move them around, creating a waste of motion. Overproduction also creates waiting as it delays the production of products that the customer is demanding. (Pereira 2009.)

Over-processing- it is considered the hardest waste to see and understand. It occurs when more work is done on a process than that is required and extra operation due to defects. It also includes using parts that are more complex and expensive than those which are necessary. It can be considered a result of poor tool or product design. (Simboli et al. 2014.)

Defects- final products that do not fulfill the required specification by the customer is a defect. It slows down the production resulting in increased lead time. It is one of the biggest threats to the company because it may happen in various forms. The absence of systematic and valid methods in the production system may allow defects to remain unidentified. It might be unnecessarily processed, which causes a high financial burden to the company and the chance of being delivered to the customer. (Dilanthi 2015.)

Skills- in the process of identifying seven defects, companies often forget the philosophy of Lean- respect for people, i.e., the recognition that a company's most valuable asset is its employees. The waste of skills happens when companies do not fully leverage the gifts and talents of their workforce. Employees might even decide to leave a company simply because they feel that they are not listened to or valued. They might consider themselves to be a number in a sea of numbers. (Pereira 2009.)

By preventing and minimizing wastes, Lean techniques allows organizations to attain many benefits; improved quality performance due to a lower number of defects and less rework, fewer process breakdowns, more involved, empowered and satisfied employees, lower level of inventory resulting in a higher level of stock turnover with minimum space required. However, detecting wastes in a process is quite a challenging task. Lean has many tools to identify and minimize these defects.

2.2 Lean principles

Following Lean methodology, the systematic identification and elimination of the sources of inefficiencies of Muda, Mura, and Muri could be done through five actions, termed principles of Lean by Womack and Jones. The principles of Lean acts as the reference point for process reorganization. The first action is defining the value through the customer's perspective. The second action is to identify the value stream for each product. The third principle states the importance of creating a continuous product flow through all the value-adding steps. The fourth action denotes creation of a continuous flow that is pulled by the customer. The last action aims at striving for perfection. These five principles must always be performed as a cycle for the continuous improvement. The 5-step cycling action is illustrated in Figure 1.

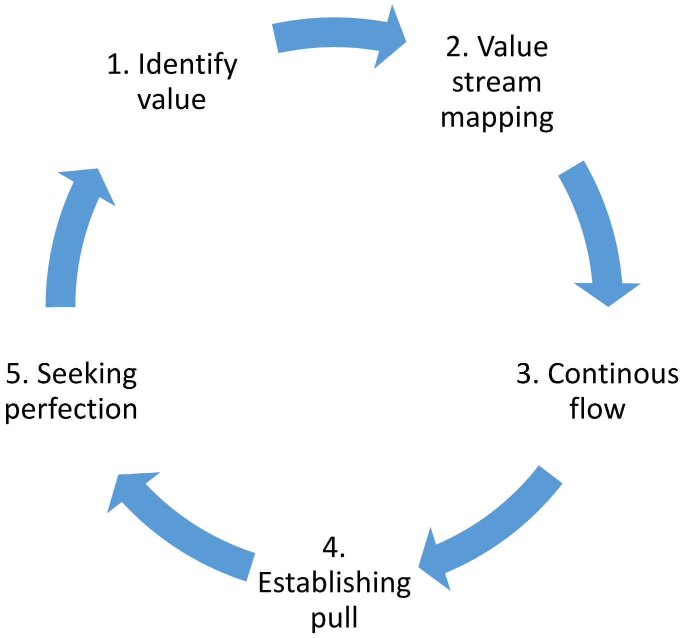

FIGURE 1. Principles of Lean Manufacturing (Adapted from Malavasi & Schenetti 2017).

2.2.1 Value

Value is what the customer wants and is willing to pay for. This requires a precise understanding of the customer's specific needs. Sometimes customer’s may not know what their wants are and might not be able to articulate them. There are plenty of techniques such as interviews, surveys, demographic information, and web analytics that can help the organization to discover what the customers find valuable. The qualitative and quantitative methods might help to identify customer's wants, the mode of delivery, and the price that they afford. Once the value is defined based on customer’s desire the priority now should be on identifying key wastes in the process as it affects the productivity and efficiency. (Mimeo 2016.)

2.2.2 Value Stream Mapping (VSM)

Once the value has been determined by the customer's perspective, the next step is mapping the value stream, which consists of the entire set of activities running from raw materials to the finished product for a specific product or product family. Value stream maps are powerful and expressive visual tools that help in the identification of wastes and to understand better the flow of materials and information (Wilson 2015). The idea of VSM is to draw a one-page map of the flow of material, the product through the process where the goal is to identify every step that does not create value and find ways to eliminate those wasteful steps. VSM is also considered as process re-engineering, which results in a better understanding of the entire business operation (Crawford 2016).

2.2.3 Continuous Flow

After the removal of waste from the value stream, the next step is to make sure that the remaining steps flow smoothly without any interferences, delays, or bottlenecks. The value-creating steps should happen in a tight sequence so that the product or service will flow seamlessly to the customer (Crawford 2016). For ensuring that the value-adding activities flow smoothly, some strategies such as breaking down of steps, reconfiguring of production steps, leveling out the workload, and creating cross-functional departments as well as multi-skilled employees could be used (Do 2017).

2.2.4 Establishing Pull

Pull production is the most critical principle of all, as it is connected to the way production is organized and conducted. Inventory is referred to as one of the biggest wastes in a production system. The objective of a pull-based production system is to minimize the level of inventory and work in progress (WIP) items while ensuring that the required materials and information flow smoothly. To attain Just in Time (JIT) manufacturing pull-based production is a must where products are created or transported at the right time, in required quantity to perform the work (Do 2017). A pull approach is, however, a demanding process as it needs accurate, adequate assessment of the market and the ability to vary products quickly on demand and requires speedy delivery of goods. A pull-based system depends highly on the effective coordination of information throughout the value stream to make everyone aware of the requirements to avoid confusion and mismatched expectations.

2.2.5 Seeking Perfection

The application of the first four actions helps to identify a considerable amount of wastes in the organization processes. The fifth principle focuses on continuous observation of these four steps as lean is about slow, steady changes, and is a continuous process improvement, which should be an organizational culture. There is never an end in the process of reducing cost, effort, time, space, and errors.

2.3 Pillars of Lean Manufacturing

Lean Manufacturing is an integrated system that consists of highly integrated elements and large range of managerial practices that follows certain sequence of implementation. Some of the most used LM tools are introduces in brief.

- **JIT**
  Just-in-time refers to the concept of having the right part at the right time in the right amount. JIT is a production methodology that aims for the improvement of overall productivity by eliminating waste, which ultimately leads to improved quality. JIT enables the cost-effective production and delivery of the necessary quality parts in the right amount at the right place and time while minimizing the use of equipment, materials, facilities, and human labor. JIT depends on the balance of stability of consumer's scheduled requirements and manufacturing flexibility of the supplier. (Abdallah & Matsui 2007.)

- **Kaizen**
  The word Kaizen is derived from a Japanese word where “Kai” means change, and “zen” means for better. The philosophy of Kaizen enables organizations to make small improvements as a result of continuous effort. Kaizen requires the participation of everyone in the organization from top management to shop floor. Kaizen refers to an incremental change rather than radical changes enabling people involved in the Kaizen activity to comfortably adapt to the changes and formalizing those changes into routine operations. Kaizen consists of three pillars, which are housekeeping, waste elimination, and standardization, and the three factors are taken into consideration for successful implementation are visual management, the supervisor’s role, and training for employees. (Maarof & Mahmud 2016.)

- **Standardization**
  Standardization is defined as the set of specific rules and operational procedures that helps in facilitating work, which is formalized (documented) and strictly followed (executed) in a production facility. The methodology aims at the elimination of variation and inconsistency by instructing employees for the execution of manufacturing activities in well-defined procedures and the introduction of rigid work standards. Standardization benefits in variability reduction that enables cost reduction and quality improvement along with employee involvement that facilitates continuous improvement. (Knudtzon 2018.)

- **Statistical process control**
  Statistical process control (SPC) is a technique to control processes that enables the identification of the cause of variation and signal the requirement for corrective actions. A controlled process is one that produces statically consistent variation and minimizes the degree of variation among its elements. SPC is built upon the following concepts: statistical, the collection of data in systematic order and is summarized, analyzed, and interpreted; process indicates a sequence of actions or methods of operation; control requires checking and measuring of performance. (Knudtzon 2018.)

- **Jidoka**
  JIdoka refers to a concept of automation with a human touch. As a technique, Jidoka stands for design principle for an automation system that aims to separate human activities apart from machine cycles to allow the operator to operate different machines in sequence. As a system, Jidoka is a specific system in an automation system that detects any abnormalities or defects and notifies about problem detection by means of "Andon" visual or audio alarm features. (Romero, Gaiardelli, Powell, Wuest & Thurer 2019.)

- **Visual management**
  Visual management is a management technique that strives for improving the performance of an organization by conveying relevant, essential, and updated information about performance, standards, and warnings through visual stimuli (Steenkamp, Hagedorn-Hansen & Oosthuizen 2017). Visual management refers to a tool to support decision-making, improve performance and promote innovation by delivery of crucial information that increases transparency and employee commitment in participating for continuous quality improvement initiatives (Glegg, Ryce & Brownlee 2019).

- **Kanban**
  Kanban refers to a signboard in Japanese, and it is an effective form of visual management for production control in the manufacturing environment. Kanban methodology is a production control system that was introduced to materialize just in time production when integrated with a pull system (Powell 2018). Kanban is a material flow control mechanism (MFC) that controls the number of products and time for production. It has been understood as a card since it uses tags to manage the delivery of parts and raw materials. The Kanban methodology uses Kanban cards and the Bin system to maintain the flow of materials in the right quantity at the right time in the place required. (Lage & Filho 2010.)

- **5S**
  The 5S lean tool aims at achieving a clean and organized workspace, decreasing the waste of time and space. The method consists of five steps in sequence. The first step is *sort*- removal of unnecessary things. The second step is *set in order*- there must be a place for all useful things, and they must be in their areas. The third step is *shine*- cleaning the workplace is essential as it reduces the risk of accidents and makes it easier for inspection. The fourth step is *standardize*- in order to optimize the first three steps standard should be created and followed. The final step is *sustain*- the final step emphasizes on developing a method to make sure that the 5S technique is followed. (Oliveira, Sá & Fernandes 2017.)

- **TPM**
  Total Productive Maintenance is a philosophy that aims at optimizing the overall performance of production equipment while ensuring their most efficient use, which is conducted by employee participation. The central concept of TPM is maximizing the productivity and efficiency of the industrial system in order to attain the highest level of productive potential or to obtain zero interruptions of the process. (Ribeiro, Godina, Pimentel, Silva & Matias 2019.) TPM is a structured process for the maintenance of equipment and ensuring the stability of the manufacturing process to ensure that the production process is never interrupted. TPM focuses on proactive and preventive techniques to improve the reliability of equipment (Gheorghe, Nisipasu, Pascu & Dumitru 2018).

- **SMED**
  Single-Minute Exchange of Die helps companies to reduce their changeover time. SMED is a methodology that is used to reduce the time machines are down during the changeover process. The SMED approach firstly identifies the external setup operations which can be performed while the machine is running and those that can only be performed when the machine is stopped, i.e., internal setup operations. The SMED has helped companies to reduce their changeover times considerably. The definition of the standards for the changeover plays a central role in applying the methodology. (Oliveira et al. 2017.)

3 INDUSTRY 4.0

The term Industry 4.0 refers to a technological evolution that works with the integration of Cyber-Physical System along with the Internet of Things and Services that brings the aspect of decentralized intelligence in manufacturing (Singh 2017). Industry 4.0 conveys a view of the future where manufacturing companies will increase their efficiency and competitiveness, through the cooperation and interconnection of their resources internally and externally with their value chain (Malavasi & Schenetti 2017).

The term Industry 4.0 is a concept that originated in Germany in 2010, and it was first introduced to the public by GEF (German Engineering Federation) in 2011 in Hannover Messe. It was initially defined as automation and digitalization of supply chains that referred a transition to a higher level of connectivity that would enable a smarter manufacturing environment. (Malavasi & Schenetti 2017.)

Industry 4.0 influences the manufacturing environment with radical changes in the execution of operations, which replaces the conventional forecast-based production planning by real-time planning of production plan along with self-optimization. The intelligent automation system in the production line synchronize themselves with the entire value chain from the order of material to the delivery of goods. (Sanders, Elangeswaran & Wulfsberg 2016.)

3.1 Philosophy of Industry 4.0

Industry 4.0 enables smart manufacturing that integrates various technologies related to manufacturing. The smart manufacturing system is the digitalization of all the components of manufacturing system by interoperability, real-time monitoring and control, flexible manufacturing, quick adaptation and response to the market changes with enhanced productivity (Phuyal, Bista & Bista 2020). Smart manufacturing is enabled by three kinds of integration which are horizontal integration referring to integration of value networks for collaboration, vertical integration that denotes the integration of different layers of automation pyramid and departments within the organization and end-to-end integration to provide newer services to the customer and data analysis from the device usage to understand the customer needs (Sony 2018). The main enabling technologies of Industry 4.0 are CPS, IoT and cloud computing.

- Internet of Things

  Internet of Things (IoT) means the network of connected physical objects (things) – devices, instruments, vehicles, buildings, and other items which consists of embedded technology that enables the objects to collect and exchange data about the internal states and the external environment. IoT allows the connected devices to sense and interact, allowing to be controlled remotely across connected network infrastructure, which creates an opportunity of direct integration of physical components into computer-based systems that would result in increased efficiency and accuracy. The connected objects, processes, and personnel make it possible for capturing of data and events that could be analyzed by companies to learn the behavior and usage pattern, react accordingly with preventive action, or augment or change the business process. IoT is considered as the core foundation for the creation of digital business. (Gokhale, Bhat & Bhat 2018; Gartner 2017.)

- Cyber-Physical System

  A Cyber-Physical System (CPS) is a combination of computation along with physical processes whose character is defined by both the cyber and physical components of the system. Embedded systems and networks monitor and control the physical process, usually with feedback loops where physical processes affect computations and vice versa. CPS is an intersection rather than a union of physical and cyber systems. Separate understanding of physical components and computational components is not enough to understand CPS; instead, their interaction is the main component of understanding CPS. CPS consists of three main parts firstly, a physical plant that is the physical part of the CPS, which includes mechanical parts, biological or chemical processes, or human operators. Secondly, one or more computational platforms consist of sensors, actuators, one or more computers, and possibly one or more operating systems. Thirdly, there is a network fabric, which provides the mechanism for the computers to communicate. Together, the platform and the network fabric form the cyber part, and the physical component is a physical part forming a cyber-physical system. (Lee & Seshia 2017.)

  Computing and communication capabilities would soon be embedded in all sorts of objects and structures in the physical world. Applications harnessing such enormous societal impact and economic benefit that bridges the cyber world of computing and communications with the physical or hardware level are referred to as cyber-physical systems. CPS are physically engineered systems whose operations are monitored, coordinated, controlled, and integrated

by computing and communication core, which will transform the ways of interaction and control of the physical world around us. (Rajkumar, Lee, Sha & Stankovic 2010.)
CPSs interacting with the physical world must operate dependably, safely, securely, and efficiently in real-time. CPS can be considered to be a confluence of embedded systems, real-time systems, distributed sensors, and controls augmented by the cyber capabilities that bring together the discrete and compelling logic of computing that enables to monitor and control the continuous dynamics of physical and engineered systems. (Lee & Seshia 2017.)

- Cloud computing
  Cloud computing is a type of subscription-based service where networked storage space, hosting services, and computer resources are provided to a client over the internet (Rountree & Castrillo 2013). Cloud computing can be defined as a model that enables ubiquity, convenient and required network access to a shared space of configurable computing resources (e.g., networks, servers, storage, applications, and services). Cloud computing is based on the idea of a very fundamental principle of 'reusability of IT capabilities (Rountree & Castrillo 2013).
  The term cloud computing was given prominence firstly by Google's CEO in the late 2006. The origin of cloud computing can be considered as an evolution of grid computing technologies. Cloud computing essentially is a bunch of commodity computers networked together in the same or different geographical locations, operating together to serve several customers with diverse needs and workload on-demand basis with the help of virtualization. Cloud users are provided with the virtual images of the physical systems in the data centers, which allow virtualization, which is a crucial concept of cloud computing as it primarily builds the abstraction over the physical system. (Rountree & Castrillo 2013.)

3.2 Design principles of Industry 4.0

With Industry 4.0 being a top priority for many researchers, universities and companies for the past few years, the contributions from academics and practitioners have not been able to make the term concrete rather, they would make it blurry. Even the principal promoters of the concept, only described the vision, the fundamental technologies to achieve the aim but could not provide a clear definition. Hermann, Pentek & Otto (2016) claim that scientific research is hindered if clear definitions are missing, as all theoretical study requires a sound conceptual as well as a terminological foundation. Design principles specifically address the issue by delivering a systemization of knowledge and portraying the components of a phenomenon. The authors were able to develop six design principles which companies should take into account while implementing Industry 4.0 solutions. The design principles enable manufacturers to investigate the potential transformation to industry 4.0 technologies.

3.2.1 Interoperability

Interoperability is one of the most critical enablers of Industry 4.0 as different systems can interact with each other and exchange data and co-ordinate activities. Interoperability enables all the CPS within the plant (workpiece carriers, assembly stations and products) to communicate among one another in such a way that unleashes the ability to use real-time data to make decisions better and faster for both humans and machines. The devices connected through IoT helps to collect and aggregate data that increases visibility hence generating opportunities for collaborations across machines and among human and machines. (Hermann et al. 2016; Swisslog 2020.)

3.2.2 Virtualization

Virtualization refers to the process of making a digital copy or shadow of machines on the factory floor or the whole factory. Through the implementation of CPS, sensors are able to monitor the physical process. The data generated by the sensors are linked to create virtual plant models and simulation models (Hermann et al. 2016). The virtualized view allows the operator to monitor the physical process in real-time and manage the growing complexity and reduce the equipment downtime enabling the possibility to optimize operations. Virtualization is a useful tool in material flow management as it allows the process controller to monitor precisely the location of the product as they move through the process that would increase accuracy and helps to identify opportunities for optimization. Virtualization enables the next level of condition monitoring of physical resources as it helps the operator to predict for maintenance to prevent failure accurately. One of the most critical aspects of virtualization is the ability it gives for industries to understand the impact of new equipment on the existing process before the actual installation of the equipment. The virtual design could precisely simulate the effect a process or equipment would have on the overall process, which allows the ability to go through what-if scenarios to understand better the resources and alternates they possess. (Swisslog 2020.)

3.2.3 Decentralization

Centralized system architectures have been the norm for material handling for years but have limited scalability in the industry 4.0 era since it cannot be expanded after a specific capacity is reached. Decentralization allows different components of the smart factory to co-ordinate independently and make decisions autonomously in such a way that they remain aligned to the single ultimate organizational goal (Ghobakhloo 2018). Self-regulating systems (embedded systems) and intelligent control mechanisms such as CPS are the critical components of decentralization which can make decisions on their own and could delegate the decision making to a higher authority during failure (Hermann et al 2016). in a distributed architecture, logic is contained in nodes which control the remote components and the subsystems. It is built with the ability to adapt according to its surrounding, communicating data by peer-to-peer communication and create its functionality and intelligence by integrating the capacities of each node (Swisslog 2020).

3.2.4 Real time capability

Data generating and collecting makes no sense if it is not analyzed in real-time. A smart factory should be able to collect real-time data, store or analyze it, and make decisions based on the findings. To be considered smart, the devices and systems of the entire production plant should know about the real-time scenario of the factory. Smart products containing RFID should be able to navigate (check for availability of the station or make alternative route) through the production plant communicating with the workstations where it needs to be and should convey the requirements of that product. Real-time capability enabled by interoperability, virtualization acts as a fuel for real-time, data-driven decision making by machines or humans. (Swisslog 2020.)

3.2.5 Service orientation

Service orientation of Industry 4.0 refers to the concepts of manufacturing as a service (MaaS) and platform as a service (PaaS). Interconnectivity among manufacturers, along with the widespread of IoT and cloud computing has enabled new manufacturing ecosystem that allow companies to communicate their manufacturing needs and capacities automatically. With the creation of this ecosystem, complex manufacturing tasks could be easily performed by the collaboration of several manufacturing services from different companies. In the PaaS business model, products are provided to customers as a service or virtual experience, which could be subscribed and paid as a reoccurring charge on the basis of usage. (Ghobakhloo 2018.)

3.2.6 Modularity

Modularity refers to a shift from inflexible, rigid and linear manufacturing to a flexible manufacturing system that has the capacity to change rapidly in ever changing circumstances and requirements. Modularity is built upon an agile supply chain, the adjustable flow of materials, flexible process, and involves the entire production and manufacturing levels (Ghobakhloo 2018). Modularity enables designing products by the organization of sub-assemblies and components as a distinct building block (i.e., modules) that can be integrated through configuration to meet various customer needs and engineering requirements (Swisslog 2020).

3.3 Pillars of Industry 4.0

Industry 4.0 aims to enable autonomous decision-making processes, monitoring assets and processes in real time, and enable real time connected value creation networks through involvement of stakeholders, and vertical and horizontal integration. Industry 4.0 utilizes technologically advanced tools to enable these features in production environment. Tools of Industry 4.0 are explained in brief.

- Autonomous Robots
  Robots are used in manufacturing to perform complex tasks which cannot be easily performed by humans. The current improvements in industries make robots less complicated to use and could be utilized in various areas such as production, logistics, distribution activities and could be controlled remotely by operators. Robots are equipped with modern sensors that enables them to collaborate with humans maintaining safety, flexibility and versatility. (Gizem 2017.)

- Big Data
  Big Data refers to acquiring, storing and analyzing a large quantity of data from different sources to increase the value-adding. Big Data can be defined by 3Vs, namely volume, velocity, and variety. BD provides opportunities in SCM as an analysis instrument to measure supplier performance and supply chain risk. (Olsson & Yuanjing 2018.)

- Cybersecurity
  Cybersecurity is a preventive solution and defense system that plays a vital role in the business environment as it prevents from harmful intents of terror attacks and data theft (Gizem 2017). Since industry 4.0 is about connecting objects with the internet to create a fully interconnected industrial network across the supply chain so, cybersecurity is required to maintain a safe, secure, and reliable communication (Ghobakhloo 2018).

- Additive manufacturing
  Additive manufacturing makes objects from a computer-aided design by depositing constituent material in a layer by layer manner using a digitally controlled and operated material laying tool (Golchev 2019). Additive manufacturing enables manufacturers to produce prototypes and proof of concept designs that simplifies and speeds up the process of new product development (Ghobakhloo 2018).

- Augmented Reality
  Augmented Reality (AR) enables visualization of computer graphics placed in a real environment, which is commonly used in the description, real-time operation monitoring, fault diagnostics, and training. This technology enhances human-machine interaction and allows motion control of its users through the use of sensor technology. (Ghobakhloo 2018.)

- Simulation
  Simulation is defined as an approximate imitation of the operation of a process or a system that requires a model development that consists of features similar to that of the system or process. The simulation will leverage real-time data to mirror the physical object in a virtual model. Simulation allows operators to test and optimize the machine specification and setting in the virtual model to check its performance before the actual changeover, reducing the machine setup time. (Rüßmann, Lorenz, Gerbert, Waldner, Justus, Engel & Harnisch 2015.)

- Horizontal and Vertical Integration
  Vertical integration refers to a process of connecting different hierarchical systems and departments among industries to achieve agility. Horizontal integration deals with the integration among the suppliers in the supply chain. (Gizem 2017.)

- IoT
  IoT serves as the infrastructure of interconnection among objects. The manufacturing system is equipped with devices that are embedded with electronic software that consists of sensors

and actuators and is connected to the internet. The IoT makes manufacturing devices to exchange data within manufacturing devices and their service provider or consumer. (Mabkhot, Al-Ahmari, Salah & Alkhalefah 2018.)

- Cloud Manufacturing

  Cloud Manufacturing refers to the modern version of cloud computing. CM is a service-oriented networked manufacturing model that converts manufacturing resources and capabilities into manufacturing services. (Mabkhot et al. 2018.)

4 RELATIONSHIP BETWEEN LEAN AND INDUSTRY 4.0

Value creation principles of LM focuses on reducing internal wastes and increasing value for the customer. Though I4.0 principles do not include these factors, it is evident that I4.0 seeks value creation by increased operational efficiency, reduced production cost, quality assurance, and creating new business models. Both LM and I4.0 assures continuous improvement of processes and products to satisfy customers. The most natural support from LM lies in the adaptation of newer technologies that have been guaranteed by the principle of continuous improvement by incremental improvements, which are operational issues. LM also emphasizes the principle automation that assists the production and implements supervisory functions through machines to detect abnormal conditions or operations. The guidelines of "firstly organize, then invest" or "first process than technology" serves as an excellent example of LM's contribution to I4.0 implementation, through ensuring of I4.0 solutions to support the value creation instead of waste generation. Through the findings of these issues, it is coherent to agree upon LM as the base for I4.0. (Vita 2018.)

Ruttimann & Stockli (2016) claim that partial and limited knowledge of Lean philosophy is the reason for the distorted ideas that Lean cannot cope with high automation. The western world's viewpoint of Lean that has been associated only with continuous improvement and elimination of waste could be considered one of the reasons for suspecting the ability of Lean to cope with highly automated I4.0 initiative. Lean is a comprehensive manufacturing theory that could be mathematically modeled. The best way to integrate these two concepts is to introduce them under the platform of CPPS (cyber-physical production system), which indicates that an organization should respect the well-accepted Lean principles in the physical world and to follow the value stream by engaging the available technologies of Industrie 4.0. (Golchev 2019.)

4.1 Interdependencies between lean and industry 4.0

Lean Manufacturing serves as the perquisite for the successful implementation of Industry 4.0 solutions as decision makers require the competence of LM for considering value for the customer and avoiding waste. Standardized, transparent and reproducible processes play significant role in the introduction of I4.0 solutions. LM focuses on the reduction of process variation and complexity that increases the efficiency and economic use of I4.0 tools (Mayr, Weigelt, Kuhl, Grimm, Erll, Potzel & Franke 2018). The technologically advanced tools of I4.0 helps Lean processes to be stabilized and increases the ability to improve the flexibility of Lean production systems. I4.0 can enhance LM by contributing to address the limitations of LM. The I4.0 helps in coping with the fluctuating market demand with increased flexibility to cope with the rising complexity. (Mayr et al. 2018.)

Dombrowski, Richter & Krenkel (2017) state that Lean production system builds the basis for Industry 4.0 and processes determine the application of a technological solution of I4.0. In the analysis, 260 use cases of German industries published on the platform Industrie 4.0 they pointed that applied Industrie 4.0 elements could be clustered into categories, i.e., Industrie 4.0 technologies, Industrie 4.0 system and Industrie 4.0 process-related characteristics. Big data, cloud computing, consumer electronics, sensors and actuators, RFID, AGV (Automated guided vehicle), and AR VR fall on the category technologies of I4.0. In the category of systems IoT, CPS, smart data, algorithms, machine-to-machine communication are included. Only after the implementation of I4.0 technologies and systems, process-related characteristics could be attained, which include elements like vertical and horizontal integration, flexibility, traceability digitalization, virtualization, etc. Analyzing the interrelation of LPS and I4.0 identification of eight principles of LPS is done, which includes zero defects, flow, pull, continuous improvement, management by objectives and employees' orientation, visual management, and waste reduction. During the interdependence analysis, waste, reduction, and cloud computing had the highest interdependence, and zero-defect principle and big data were highly interdependent. (Dombrowski et al. 2017.)

4.2 Correlation between lean and industry 4.0

The LM and I4.0 could coexist and support each other and are compatible to each other. Both manufacturing systems have similar concerning targets like the reduction of complexity and increase in productivity and flexibility (Mayer et al. 2018). I4.0 can complement LM by helping companies to deal with flexible production systems and industrialization of customized products within volatile demand. The correlation between LM and I4.0 is significant and positive. Experience of LM provides significant contribution on I4.0 and same is the vice-versa. The integrated approach of I4.0 and LM has positive influence on organizational performance which is higher compared to the influence of each approach implemented in a stand-alone way. (Vita 2018.)

4.3 Sustaining and disruptive changes

Industry 4.0, with its technological advancement, is sure to bring some changes in the existing pillars or foundations of Lean. Malavasi & Schenetti (2017) analyzed the changes that I4.0 will bring in pillars of Lean. They explained the sustaining and disruptive changes I4.0 tools would bring in the context of LM. Those changes or innovations that bring dramatic changes or disruptions in the existing trends are called disruptive changes. These changes often lead to a redefinition of products or business models, radically changes the concept of value for consumers that enables them to displace existing and established businesses. Sustaining innovations replace older trends with slightly improved versions. Though sustaining innovations have a zero-sum effect on jobs and capitals, they are significant economically as they keep the margins attractive and the market vibrant. (Malavasi & Schenetti 2017.)

1. Stable and standardized processes
   Standardization work includes methodologies such as takt-time (rate at which the production process should be completed in order to meet the customer demand) and precise work sequences. Standardization serves as the foundation for continuous flow and pull production. Standardization plays a crucial role in I4.0 as well. The principles of I4.0 that sustain standardization are interoperability and modularity, whereas MaaS (Manufacturing as a Service) seems to be a disruptive change in terms of standardization as companies are not focused on production-oriented processes but service-oriented ones. Cloud manufacturing creates a new way of doing business where companies can rent production capacity and capability when needed. (Malavasi & Schenetti 2017.)

2. Visual management
   Visual management in the context of I4.0 would have higher sustaining aspects as I4.0 would enable the real-time capability. Human Machine Interface, Augmented Reality, Virtual Reality, and smart devices would enable a higher level of visibility in the factory. (Malavasi & Schenetti 2017.)

3. Just in Time
   JIT is one of the central pillars of LM, which advocates for the production of the only necessary parts in the required quantity at the necessary time using the minimum amount of resources. JIT would be sustained by cloud computing. With the use of cloud computing JIT will move towards a digital viewpoint as data within a factory would be collected by tracking devices and by fostering of their synchronization and real-time sharing in the supply chain through cloud platforms providing the right information at the right place at the right time. Industry 4.0 can also bring

disruptive change in terms of JIT by smart manufacturing technology, i.e. additive manufacturing. (Malavasi & Schenetti 2017.)

4. Jidoka
   Advanced automation is a feature of I4.0, so, this aspect can be represented as an evolution of Jidoka concepts. Collaborative robots used in production indicates to a sustaining viewpoint to Jidoka, whereas CPS depend upon the synergy of cyber and physical components is supposed to be disruptive aspect associated with jidoka. (Malavasi & Schenetti 2017.)

5. Waste reduction
   Waste identification and reduction serve as the basis for LM. Traditionally Lean uses methodologies such as Genchi Genbutsu, Five Why's to identify and remove waste. Industry 4.0 offers sustaining changes to waste reduction by supporting factories improvement by waste reduction employing IoT, Big Data, and analytics. (Malavasi & Schenetti 2017.)

5 EXISTING MODELS OF INTEGRATION

The capability of integrated LM and I4.0 is associated with two skeptic dilemmas. Firstly, the fitness of Lean to perform in the context of higher volatile customer demand and non-repetitive production environment. Secondly, LM has been used to focus on the simplicity of production in series, whereas I4.0 increases the complexity and level of customization with a shorter product life cycle. (Vita 2018.)

5.1 Grouped dimensions of Lean manufacturing

Sanders, Elangeswaran & Wulfsberg (2016) presented an approach to overcome the barrier for implementing Lean by Industry 4.0 technologies. The authors bridge the gap between the two realms of LM and I4.0 by identification of the exact aspect of I4.0 contributing to the dimension of LM. Commenting into I4.0 makes a factory Lean besides smart manufacturing capability by advanced application of information and communication technology in manufacturing that enables mass customization. The authors claim that I4.0 is equipped with high-end solutions that possess the necessary tools to implement Lean. LM and I4.0 are not mutually exclusive and can be seamlessly integrated with each other for successful product management. For the integration purpose the widely accepted, ten dimensions of Lean are validated for attainability through technologies of I4.0. These ten dimensions are grouped into four significant categories depending on the entities involved in each dimension.

Supplier factor

It is concerned with the flow of goods and information as it needs to get synchronized with the changes in the business process of the manufacturer. To create a continuously improving Lean ecosystem, all partners in the supply chain need to develop with the manufacturer to avoid any mismatch of goods and information flow. In the context of I4.0, technological networks are established between cooperating partners where they could share information and data, as well as manufacturing machines and human experts. The resources are owned by different organizations but act towards a common objective. Suppliers need to be informed about the status and condition of products and services provided by them as it creates an environment for immediate response and actions during any discrepancies. I4.0 provides the necessary tools to share data of products and processes beyond the individual boundaries of industries enabling them to synchronize. Cloud computing and mobile computing services renovate the traditional communication mechanism. These technological tools of I4.0 help to develop suppliers and maintain useful supplier feedback. JIT delivery by suppliers plays a significant role in enabling LM, and with the help of IoT, transparency during transportation could be achieved. Tagging of every item ensures sending the right product to the correct location that reduces the lead time of distribution. (Sanders et al. 2016.)

Process factor

Lean emphasizes on performing any operation only when demanded by the customer. The essential factor for LM is pull production, which is based on Kanban. By the use of ICT, an e-Kanban system recognizes any missing and empty bins automatically via sensors and triggers a replenishment action. An inventory control system in real-time can monitor the e-Kanban. (Sanders et al. 2016.)

The flow of materials should be continuous according to a determined value stream that should arrive only at a required time to maintain a streamlined flow of operations. Errors in inventory counting, capacity shortages, and centralized control systems leading to delays in decision making disrupts the flow. I4.0 solutions employing RFID help in eliminating errors and increase visibility through real-time tracking of inventory. Decentralization helps in an optimized material distribution plan by elimination of interruption and waiting. (Sanders et al. 2016.)

With the diversification of customer demand, the variants of products also delivered increases that require a changeover of parts. While modern manufacturing is proceeding towards mass customization industries, it needs to reduce setup time between variants. I4.0 offers plug and play and distributed systems that are equipped with self-optimization and machine learning behaviors that enable firms to adapt machines according to products and enable small batch production. With the RFID technology products, communicate to the respective machine that helps in the quick changeover of machine parameters. (Sanders et al. 2016.)

Customer factor

Customer involvement in the process of product development ensures that the customer need is fulfilled. The customer requires to be informed about the actual production stage and the expected delivery time. Business models are converting into providing products along with services that help to discover new customers while increasing the experiences of the existing customers. I4.0 employs intensive techniques for market research and customer analysis. Big Data helps in performing incredibly complex calculations to understand the relationship between needs and functions. Smart products are integrated with devices that track the usage of data and send to producers to better identify customer's needs in-order to provide more suitable products and solutions. (Sanders et al. 2016.)

Control and human factors
The Failure of machines during production adversely affects the schedule of production, which is why companies follow preventive maintenance routines. With more advanced analytics and big data offered by I4.0, machines are equipped with the ability to anticipate potential breakdowns and be self-aware of the issue and identify the root cause and be self-maintained. (Sanders et al. 2016.)

The quality of products is considered as prime importance in the manufacturing industry and should be under control. The ignorance of operators during operation and the inability to track the variation in the process contributes significantly to decreasing the quality of products. In the context of I4.0 products come with details about the required operations and the sequence of operations required on them. RFID, IoT, and advanced analytics increase business intelligence by computing meaningful trends and relationships from the available data. (Sanders et al. 2016.)

Employee empowerment has a significant effect on the successful execution of LM as they are responsible for the actual work of creating products and services. Employees should be provided with an adequate amount of flexibility and the importance of acknowledging their ideas and suggestion as they are the participants of a continuous development process. In the workplace environment of I4.0 workers could provide their suggestions and feedback immediately by means of smartphones and tablets. The manager could quickly check the availability and allocate workers to different operations through handheld devices. Thus, smart feedback devices, along with the improved human-machine interface and worker support systems, enable better empowerment of employees and increases their involvement in the organization. (Sanders et al. 2016.)

5.2 Vertical, horizontal and end-to-end engineering

The model developed by Sony (2018) is an integrative implementation framework that describes the steps required for any organization to integrate both the concepts of I4.0 and LM. The integration model is guided by the principles of LM, which emphasize the application of five LM principles to strategize the best possible combination of sequence for integration. The author elaborates on the necessity for the elimination of waste by LM principles before the implementation of three integration mechanisms i.e. vertical, horizontal, and end-end engineering integration, to avoid automating the waste generation. (Sony 2018.)

The vertical integration is the process of creating a flexible and reconfigurable manufacturing system by the integration of various hierarchical elements and subsystems within the organization employing digitalization. The first step in this integration is the identification of value. Defining the value in terms of customer requirements forms the underlying principle for vertical integration. Value stream mapping of the products and services before the designing of the architecture of vertical integration helps in the removal of waste and integration of CPS. The vertical integration of different subsystems creates a smooth flow that leads to cross-functional cooperation among departments by CPS integration by the use of a self-regulating system. The integration within the organization reduces the time to bring a product into the market, enabling a pull system created by the demand. The integration should create a continuous improvement culture to increase value to the customer. (Sony 2018.)

The horizontal integration is the integration of value networks between the corporations and organizations to enable smooth coordination in the value chain. A successful business requires the cooperation of multiple organizations to deliver useful products or services. Horizontal integration of various organizations is designed upon the mutually agreed perception of the customer's value among the participating organizations, which the agreed integration strategy is supposed to achieve. Incorporating VSM helps to identify waste in the horizontal integration mechanism. The flow across the cooperating organization will improve by incorporating smart coordination and regulatory system. The horizontal integration mechanism will enable to deliver customized products and services in the shortest possible time based on a customer triggered pull system. To provide the optimum value to the customer by using minimum resources, all the horizontal integrated organizations should create a culture of continuous improvement. (Sony 2018.)

The end-to-end engineering integration facilitates the creation of customized products and services across the value chain. End-to-end engineering integration requires identification of customer perceived value. The value stream of CPS system requirements helps in the identification of non-value adding activities. The data from the smart product could be used to design smooth flow by the use of CPS. The data from the smart product can be used to design a pull system. The self-regulating mechanism from smart data of the products will create a culture of continuous improvement. (Sony 2018.)

6 CONCEPTUAL MODEL FOR INTEGRATING LEAN AND INDUSTRY 4.0

The conceptual model of integration of LM and I4.0 will be based on philosophy, principles and pillars-based integration. To make this model easier literature on LM and I4.0 were studied based on Philosophy, principles and pillars. Each level of integration is examined in the following sub chapters.

6.1 Philosophy integration of LM and I4.0

The philosophy of LM emphasizes analyzing the value and waste. Any work that does not add value to the customer is waste. The philosophy of Industry 4.0 is to create a smart factory that is vertically, horizontally, and end-to-end engineering integrated. The value that has been brought in the context of the smart factory is analyzed in three level of integration. Value of three level of integration is illustrated in table 1.

The vertical integration of the different hierarchical layers and departments of the industry enables higher operational intelligence. Using CPS, IoT, and Cloud computing technologies, the assets of the organizations can communicate machine-to-machine and human-to-machine giving rise to a new relation. The autonomous systems are equipped with Big Data and analytics that enable the machines to analyze the data and optimize the process based on the production requirements. By the use of CPS and RFID the products could store information on them, enabling the machines to read the specification and perform the specified operation. The real-time capability enables the condition monitoring of the machines in real-time and perform diagnostic functions and solve them. Using AR tools, operators could be assisted by technicians to perform maintenance work, hence enabling remote maintenance. Products could navigate through the machines triggering required operations.

The horizontal integration of the value stream enables coordination and cooperation among the supply chain. Technological advancement offered by I4.0 tools increases the transparency among the value chain network reducing the mismatched delivery of materials and services. Real-time monitoring of goods enables a continuous and streamlined flow of materials maintaining a balanced JIT delivery of goods. The use of RFID allows track and trace of goods in the facility that helps in maintaining the inventory and transportation management within the premises or beyond.

Smart products are equipped with sensors that can store information about themselves in terms of manufacturing, current status, circuit diagram, and assembly information. The CPS helps to convey the information that could be analyzed in order to understand the customer requirements better. The CPS enables us to understand customer usage, which could help in the betterment of the product life cycle management and software updates.

TABLE 1. Value identification of smart manufacturing (author's own interpretation)

Industry 4.0 / Lean	Vertical integration	Horizontal integration	End-to-end engineering integration
Value	*Operational intelligence *Advanced process control *Energy management *Condition monitoring *Remote maintenance *Process simulation	*JIT logistics *Inventory management *Track and trace *Warehouse management *Transport management	*Product lifecycle management *Collaborative engineering *User consumer experience *Remote software update

Waste identification and elimination is a continuous process that helps to keep the flow streamlined and to acquire a state of JIT delivery of goods. Technological advancement of I4.0 enables to identify wastes that were not possible to recognize and eliminate manually. Traditional seven wastes identified by the LM could be reduced by the use of digital tools of I4.0. Different tools of I4.0 helps in the identification and removal of different forms of wastes (Satoglu, Ustundag, Cevikcan & Durmusoglu 2017). Wastes identified and reduced by tools of I4.0 is illustrated in table 2.

TABLE 2. Seven wastes and Industry 4.0 technologies (Adapted from Satoglu et al. 2017)

	Additive Manufacturing	Augmented Reality	Virtualization	Autonomous robots	IoT	Data analytics	Cloud Computing
Transportation		X	X	X		X	
Inventory	X	X			X	X	
Motion				X			X
Waiting	X		X	X	X	X	X
Overproduction	X				X	X	
over processing	X		X	X			X
Defects	X	X	X	X	X	X	

6.2 Principles integration of LM and I4.0

Customer's requirements are ever-changing so, companies need to develop ways to meet customer requirements and create value. Due to the digitalization of the purchasing process, the market development and customer influences will increase with the advancement of industry 4.0. The smart products are integrated with devices like the RFID tags that enable tracking of customer usage data in real-time that could be analyzed by Big Data to understand customer needs. The flexibility of customer demand is also enhanced with service-oriented architecture. (Valamede & Akkari 2020.)

Virtualization enables digital simulation of the VSM, enabling decentralized engineering design decisions. By the help of Big Data and Analytics information is updated in real-time that could aid in eliminating wastes. Through Cloud Computing, the VSM information could be accessed by different stakeholders of horizontal integration. (Valamede & Akkari 2020.)

Materials could be tracked in real-time using RFID tags, which enables a low level of inventory and timely order of products. Operators equipped with augmented reality glasses and smart devices could easily follow the operation instructions required by the product to maintain the flow. Autonomous robots and cobots (collaborative robots) are able to identify product errors and act accordingly. Capacity shortages could be addressed through subcontracting by means of service orientation. Flexible, distributed, and autonomous production can be attained by decentralization and modularity, maintaining the continuous flow of goods. (Valamede & Akkari 2020.)

The real-time capability allows the precise tracking of products and processes. With the help of Big Data and decentralized decision making, the intelligent plant becomes self-organized. The robots and AGVs can notify the CPS through interoperability for the replenishment of the required resources. With the help of virtualization virtual maps are regularly updated with information from the supply chain. (Valamede & Akkari 2020.)

Machines are connected to the internet to analyze the data and are provided with operational intelligence that could provide data on production flow, the condition of the equipment and failure notifications. By the use of Big Data and virtualization, decentralization could be achieved to create an alternative route for the betterment of flow. (Valamede & Akkari 2020). The interaction among the principles of LM and I4.0 is illustrated in table 3.

TABLE 3. Principles integration of LM and Industry 4.0 (Adapted from Valamede & Akkari 2020).

	Design principles of Industry 4.0					
Lean Principles	Interoperability	Virtualization	Decentralization	Real-time capability	Service orientation	Modularity
value	X			X	X	
Value mapping	X	X	X	X		
Flow	X	X	X	X	X	X
Pull	X	X	X	X		X
Continuous Improvement	X	X	X	X		

6.3 Pillars integration of LM and I4.0

The pillars or tools of LM and I4.0 could be studied as tool-based approach, resource-based approach and reduction of waste-based approach. Certain technological tools of I4.0 would sustain the LM pillars whereas some would disrupt. The pillars integration is based on Lean-wise, which means that the emphasis is put on I4.0 tools implementation towards LM tools.

JIT and I4.0

JIT aims at delivering the right product at the right amount at the right time. AGV transports the required resources at the workstations that optimizes the material flow and minimizes the error. Intelligent bins and smart products store information on them, lowering the possibility of a mismatch. RFID enables the monitoring of all the assets, including raw materials shortening the search time, increasing transparency, and helps in maintaining inventory levels and the automatic replenishment process for suppliers. Big Data analytics helps to identify trends. A continuous flow is enabled by the reduced machine downtime with the help of predictive maintenance. Suppliers in the horizontal integration benefit from real-time information sharing.

Kaizen and I4.0

The smart factory is interconnected with any processes that do not add value or creates waste that could be identified. The vertical, horizontal, and end-to-end engineering integration layers collect data that is analyzed and optimized by the help of smart sensors, cloud computing, Big Data and analytics, and machine learning.

Standardization and I4.0

Standardization aims at eliminating variances and inconsistency by following strict standards at work. Machines that can communicate with each other can communicate about the fixed parameter of the product. The smart product comes along with the specific instruction and steps to be followed on it. The interoperability of machines allows communication.

Statistical process control and I4.0

Statistical process control helps in-process monitoring and variation reduction. The advanced automation in industry 4.0 is equipped with sensors to track any variations in the production. Big Data and analytics could monitor the variation in real-time, and error-proofing could be done.

Visual management and I4.0

Visual management is used to increase transparency in the organization. The standards and specifications are displayed using smart devices. Any information that needs to be displayed could be easily displayed in real-time. Information like machine condition, productive progress, order status, and capacity utilization could be displayed.

Kanban and I4.0

Kanban is used to maintain an uninterrupted continuous flow of materials, maintaining a defined stock. With the help of virtualization, a simulation model can identify the Kanban parameters like the lot size, stock, and delivery frequency. With real-time capability, external changes could be included autonomously. By the use of e-kanban, the transparency of material can be increased, and replenishment could be automated, enabling reduction of stock level.

5S and I4.0

5S represents the systematic approach to organize the workplace that helps in keeping the workplace clean and arranging tools in a reasonable way. RFID tags and AR (Augmented Reality) could assist in implementing effective 5S. RFID helps in the identification and locating of objects. AR could help the operator to find the right place to keep tools.

TPM and I4.0

Industry 4.0 implements many solutions to support TPM. The productivity of any factory depends on the machines used in the process. The automation systems in industry 4.0 can self-monitor their status and self-optimize. Tools like AR and VR allows training as well as maintaining instructions that could be guided remotely.

SMED and I4.0

SMED is used to reduce change over time. To reduce the setup time Industry 4.0 uses tools like plug and play, modular manufacturing, and additive manufacturing. With the increase in variants, additive manufacturing is expected to achieve the highest impact on set up time reduction.

7 CONCLUSION

Above a brief description about Lean Manufacturing and Industry 4.0 have been plotted. Based on the study it could be concluded that Lean Manufacturing and Industry 4.0 are positively related. Lean Manufacturing serves as the foundation for Industry 4.0. The true potentials of Lean Manufacturing could be achieved by the technological advancement offered by Industry 4.0. The combination of Lean Manufacturing and Industry 4.0 promises smarter and more intelligent manufacturing systems which is required to satisfy consumer needs in present times.

The integrative model describes how Lean Manufacturing and Industry 4.0 could mutually contribute and be of benefit to each other. The integrative model supports strategic, operational and functional integration of Lean Manufacturing and Industry 4.0.

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