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Industry 4.0 Technologies and Lean Production Combination: A Strategic Methodology Based on Links Quantification

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ABSTRACT

The current environment faced to economy and sustainability requirements brings to the fore two paradigms sustaining the industrial performance: Lean Production (LP) and Industry 4.0 technologies (I4.0). Whatever business the companies run they have to consider the benefits of both. The methodology of this paper is based not only upon combined analysis identifying nature of links but also on quantifying these links in order to provide a dashboard with Key indexes helpful for decision makers. It involves a strategic method to figure out the technologies and Lean tools deployment priority. It consists in an attempt to quantify links providing a method based on Layers analysis for modular implementation and an approach to settle calculation of an actionable elements. Indicators comes out for strategy deployment: Index of relevancy and Index of coverage. They are built to increase the visibility, followed by modular implementation proposal and Expansion index to allow monitoring. At the end, the industrial managers initially attempting to deploy Lean and industry 4.0 with reserve impressed by these giant transformations, will beneficiate of a structured roadmap (algorithm-based) culminating to the priority of the implemented tools and technologie

1. INTRODUCTION

To improve the performance of industrial systems and boost the production efficiency, an increasing number of companies around the world and in various sectors are undertaking the implementation of Lean from workshops to whole enterprise and even global supply chain (Da Silva et al., 2020; Nounou et al., 2022; Possik et al., 2022). Lean is considered as a methodical approach to organize and optimize the production flow aiming at realizing a continuous value stream to increase the quality and improve the reactivity while reducing the wastes and non-value-added activities. Lean is a mature approach used for more than 70 years in Japan and more than 40 years in Europe. Possik *et al.* (2021) demonstrate that Lean tools should not be used in a monotonous way but that their usefulness depends on the considered economic context of the company.

Besides, Industry 4.0 is a global concept aiming to design and create the enterprise of the future and smart factories. Named differently in the literature (industry of the future, smart factory, industry 4.0) and according to the strategic national programs (Industry 4.0 in Germany 2011, Industry of the future in France 2014, Fabrica intelligente 2013 in Italy, Made in China 2025, Future vision Japan 2030), all those initiatives target the common idea of building smart factories, connected and reconfigurable using various technologies. It focuses on the technology-driven vision combining the physical world and the cyber world through specific web and digital technologies (Eleftheriadis and Myklebust, 2018). Industry 4.0 grasps the

attention of many researchers and practitioners (Cagnetti *et al*., 2021; Küfner *et al*., 2021; Titmarsh *et al*., 2020; Bittencourt *et al*., 2021). Indeed, there is an urgent necessity to clarify the methodology of its implementation because no structured and well-defined model nor
method yet exist (Prinz *et al*., 2018; Sony, 2018; Zhang *et al*., 2017). Few attempts have defined standards useful to identify the scope and the main fundaments. Xu *et al*. (2018) remind the first community efforts to standardize the comprehension, namely Reference Architecture Model for Industry 4.0 (RAMI 4.0) has been introduced by the German Electrical and Electronic Manufacturers' Association (Rojko, 2017). RAMI 4.0 introduces a three- dimensional coordinated system that describes all crucial components of Industry 4.0. Within this system, complex and complicated interrelations can be decomposed into subsystems, clusters, or modules (Götze, 2016).
Both approaches contribute to close similar targets. Lean manufacturing aims to reduce time, increase quality avoiding defect products and decrease costs while maintaining safety target and worker motivation (Amrani and Ducq, 2021). Industry 4.0 adds elements of customization, new business models and connected systems (Enke *et al*., 2018; Da Silva et al., 2020). Prinz *et al*. (2018) point out that both paradigms have often been considered as separate subjects. Some authors catch the idea to associate both but in unilateral analysis with the necessity of Lean as a prerequisite for Industry 4.0 (as shown in Figure 1). The possible gain when I4.0 is implemented after LP is highlighted and new long-term increase in productivity with no saturation point is observed.

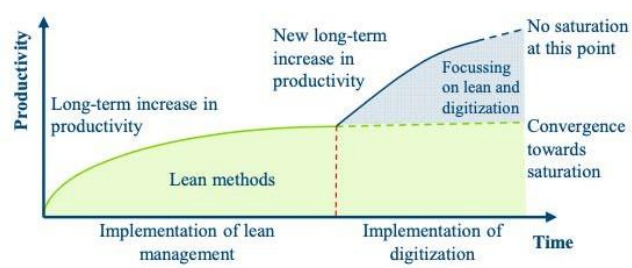

Figure 1. Impact of implementation of Lean before Industry 4.0 (Prinz *et al*., 2018)

The sequential implementation of new improvement axes shows that it is of upmost importance to apply Lean as a prerequisite for Industry 4.0 implementation (Powell *et al*., 2018; Eleftheriadis and Myklebust, 2018). Satoglu *et al*. (2018) consider the combination of both approaches and suggest that *"lean and industry 4.0 are not mutually exclusive but can be combined, however, the combination is yet very primitive with direct dual combination of effects without global model".* It is often stressed that a minimum maturity in Lean is advised before introducing digitalization, to achieve the expected results (Buer *et al*., 2021). Lean should be well performed before automatization and connection. This is interesting to state that Industry 4.0 does not substitute to mismanagement and weak organized manufacturing. It is worth to denote that exclusive link with unilateral analysis is not enough anymore. Mayr *et al*. (2018) evoke the possible conjunction between both research axes. Mrugalska and Wyrwicka (2017) review some examples of leading Lean and Industry 4.0 in conjunction. Rossini *et al*. (2019) relate relevant findings indicating that European manufacturers who aim to adopt higher levels of I4.0 must concurrently implement Lean as a way to support process improvements. Powell *et al*. (2018) evoke Industry 4.0 technologies as enablers of leaner production.

2. LITERATURE REVIEW

LP and I4.0 are co-existing study domains. They are cross-analyzed but not integrated together in a common approach of analysis with a view to performance improvement (high quality, flexibility, rapid reaction, customer service) (Santos *et al*., 2021). However,
interlinking LP and I4.0 becomes difficult to apprehend. The enabling effect is claimed but no mature methodology exists to reveal how it happens (Ciano *et al*., 2020). In the next section, a state of the art is browsed to get an overview about the global tendency and draw a picture of the actual research landscape. By Lean mentioned in this study, we refer to the Lean Production tools.

a. Lean and Industry 4.0: Research About Integration

The relationship between LP and I4.0 technologies can be seen along two distinct paths corresponding to two kinds of approaches that we have identified from the literature.

The table 1 synthetizes significant authors results. Some contributions correspond to the Path 1 (LP first) while the other ones follow the path 2 (I4.0 first). Main managerial insights are summarized. The papers selected for this synthesis were judged to be representative and recent enough to appear. Key words were: Lean, industry 4.0, technologies, digitalization and Production. We have browsed Elsevier, Scopus, Springer, Web of Science and Emerald (through internal university database) to study research papers.

Studies Combining « Lean Production » and « Industry 4.0 technologies »

Authors	Main Outcomes		
	Path .1: I4.0 Technologies benefits to Lean	Path.2:Lean benefits to I4.0 technologies	Managerial insights
(Pereira et al, 2019)	✓ I4.0 empowering LM ✓ CPS provide real-time data enabling instant KPI feedback. ✓ 3D printing enhances JIT: decreases lead time and increases logistics efficiency. ✓ Cloud: real-time information will enable managers in their decisions, reduce waste and minimize business risk. ✓ CPS symplyfies the use of Andon and Kanban	-	✓ Literature analysis of the I4.0 tools that are empowering Lean practices:CPS,IoT,BD,Cloud,VR and AR,Robotics,3D printing and simulation. ✓ 54 articles analyzed, 55% relates I4.0 empowering Lean. ✓ I4.0 technologies allied with lean can reduce non-value adding activities ✓ I4.0 technologies ensures data collection,comunication, information capability and data display useful for Lean.
(Rosin et al., 2020)	✓ I4.0 reinforce the efficiency of Lean principles. ✓ Most commonly used tech to improve lean: ✓ IoT,Simulation,Autonomous robots,BD. ✓ Most improved lean techniques with I4.0 :JIT and Jidoka	-	✓ Table linking the TPS house diagram and I4.0 tech. ✓ I4.0 does not cover/ replace Lean management approach.
(Ciano et al., 2020)	✓ Empowering effect of I4.0 on LP ✓ One-to one relationships between I4.0 and Lean classify by: Supplier, Manufacturing and customer ✓ Smart Machines empowering Andon,SMED a ✓ Product simulation empowering Kaizen ✓ Cobots in U-cell Shape allowed continuous flow	✓ The enabling effect of LP in the technology of I4.0 ✓ VSM enables I4.0 vertical integration.	✓ Lean production process based facilitates the environment for the introduction of I4.0 ✓ Lean production techniques might help in problematics lead by a premature introduction of I4.0 technologies. ✓ LP if not applied before introducing will turn into a digitalized waste system.
(Bittencourt,2021)	✓ Lean process capability improved through integration of industry 4.0. ✓ 100% of the documents review in literature highlight the support of I4.0 on lean ✓ At least half of the documents analyzed indicates the enabling effect of lean in I4.0	✓ Only 45% of the documents review in literature highlight the support of Lean on I4.0 technologies	✓ To obtain better performance results when implementing I4.0, lean process mapping is recommended. ✓ Increased of operational performance when implementing I4.0 if there is a solid Lean System ✓ Integrate human factors in the model of I4.0 implementation.
(Buer,2020)	✓ Lean tools more likely to be impacted by I4.0: TPM, Kanban, production smoothing and waste elimination.	✓ The paper shows that having a high lean implementation level results in a positive impact with factory digitalization.	✓ Concurrently implementation of I4.0 and Lean is strongly advice to support process improvements. ✓ The use of digitalization and LM produces a synergistic effect on operational performance.
(Akkari,2020)	✓ Circular Layered diagram indicating how I4.0 enhance LP ✓ Several outcomes: JIT, Kanban, Poka-Yoke ,VSM, Kaizen, TPM ✓ 42 possible relationships between I4.0 and lean were identified, where, 25 of this represent the synergy between them.	-	✓ The combination of JIT 4.0 and cloud provides real-time data and translated in information for better management. ✓ Virtual Simulation allows multiple mapping possibilities for managers to analyze before implementing any solution.
(Salvadorinho,2021)	✓ Kanban, jidoka, VSM, SMED, TPM, and KPIs have been integrated with digital word ✓ Visual Management 4.0: empowered by IoT saves time for manager through digital boards. ✓ Smart visualization allows prediction of future accidents	✓ VSM is the tool with more practical applications, therefore, it has more evidence of possible connections with I4.0 technologies. ✓ Minimum maturity of lean practices is necessary when implementing I4.0 technologies.	✓ IoT is commonly used to improved real-time tracking eliminates unnecessary movement. ✓ 77% of the articles indicate I4.0 empowering Lean ✓ Having a minimum maturity of lean allows to reach easily the expansions of I4.0 implementation.
(Santos et al., 2021)	✓ 4 solutions of Industry 4.0 are retained (CPS, Simulation, Big Data Analytics, HMI) ✓ Association of Technologies to Lean Tools is suggested.	-	✓ The combination of LP and Industry 4.0 solutions is targeting to improve: Leadtime, traceability, connectivity and reliabily

Authors quoted in Table 1 attempt cross-analysis among LP and I4.0 technologies. Each author adopts his own vision and we can argue a necessity to be the most exhaustive possible in the analysis in terms of tools to be considered. For instance, Akkari and Valamede (2020) quote Kanban, Poka yoke, VSM, Kaizen and TPM but do not consider Smed, Ucells, 5S and many others. Rosin *et al*. (2020) treat IoT, AGV, Simulation but not 3D, RFID, Digital twin and many other technologies. Wagner *et al*. (2017) mislead technologies such as Digital Twin, 3D, IoT that we nevertheless consider essentials. From Lean side, Value Stream Mapping, which is a powerful Lean tool (Santos *et al*., 2021) is not considered and others yet miss such as Ucell, Heijunka, … Obvious necessity of consistent study and significant huge cross- analysis is yet necessary.

b. Leading Industry 4.0: Case Studies Benchmark

When dealing with implementation of Industry 4.0, browsing the existent case studies embracing digital transformation is obviously necessary. We have chosen to build a synoptic on some chosen companies leading digital transformation with different levels of commitment.

It is interesting to perceive the vision on behalf of those who were leading successfully this transformation. They can be considered as best in class serving as benchmark to refer barriers to overcome and success factors to pursue as learning points. The sample for this benchmark has been intentionally chosen among big groups (more than 5000 employees). Indeed, big companies have made a step up with the arrival of new technologies, we judged important to draw a feedback to inspire decision makers. We focus our panel in automotive, electronics and aeronautics. Moreover, documentations about that companies are fallen in the public domain and no confidentiality obstructions prevent from publishing. These companies have also been discussed in the scope of European project I4EU

(Traoré et al., 2021).

The table 2 gathers the various implementation approaches of well-known, documented industrial cases with public data. The vision of each company can be appreciated, the used technologies are highlighted. These findings may constitute useful insights for practitioners to get at glance a quick and useful understanding of the key significant alert points.

The industrial progress of companies committed in Industry 4.0 encompasses main concepts of *"connectivity",* as can be seen in *Siemens*, *Bosch*, *Schneider* and *Ericsson*, the notion of *"digital"* in *General Electric*, *Dassault* and "*IoT*" in *Latecoere*, *General Electrics* and *Honeywell*. Widespread technologies are used by different stakeholders. They are specific to sectors requirements and contextualized to the strategies of groups. When a company is willing to commit in Industry 4.0 transformations, it must be aware of the key barriers:

- *Data security* (*Siemens* reminds cybersecurity, *Bosch* outlines privacy concern, security roadblocks in *Dassault*),
- *Culture lack* (*Siemens*),
- *Skills lack* (digital skills in *Siemens*, users' unawareness in *Dassault*), and
- *Budget/cost threat* (access to finance evoked by *Siemens*, implementation cost in *Bosch* and *Dassault*).

The readiness to transformation was also a critical point:

- Readiness of workforce (*Bosch*),
- Lack of culture of industry 4.0 (*Siemens*),
- Missing of implementation know-how (*Schneider*), and
- Lack of knowledge in technology (*General Electric*).

The transformation to lead is difficult, from one hand, because of the choice of the technology and, in the other hand; because the deployment is hard, even when the technology is chosen (as quoted in *Schneider* and *Honeywell*). Business complexity (*Honeywell*), with its various processes to optimize, adds difficulty. *Latecoere* and *Dassault* remind the necessity to deploy Lean to create safe and efficient processes before optimizing their connectivity.

Table 2. Benchmarking Industry 4.0 transformation key points – Industrial applications

Benchmark – Big Companies leading Industry 4.0 transformation

Case Study	Vision of Industry 4.0	Technologies Used	Barriers	Key Sucess Factors
Siemens	✓ **Ubiquitous connection** of people, things and machines (Geissbauer,2014) ✓ **Continuous digitalization** of the value chain (Geissbauer,2014)	✓ Siemens plan **Cloud services** (Siemens official site, 2020) ✓ Siemens plan cloud **analytical services** ✓ **Digital Tools:** NX-Computer aided design, CPDM-Collaborative product data management, DM-Digital manufacturing, MES, Manufacturing execution systems, C&C-Command and control	✓ Digital **skills** ✓ Access to **finance**, scale of investment ✓ Data and **cybersecurity** ✓ Lack of **access to proof** points (Siemens Financial Services ,2018)	✓ Address growing digitalization skills requirements through **Outsourcing.** ✓ Coherently assess the **aspects of a manufacturer's business** (Siemens Financial Services ,2018) ✓ A **culture of collaboration** must be implemented. (Siemens Financial Services ,2018)
Bosch	✓ Summed up in three letters S: 3S for **"Sensors, software, services"**, sensors for reporting product information, software for analyzers and treat, and services for **ultimate connectivity.** (Hogh-Binder,2017) ✓ The new generation of infrastructure, of power plants, power grids, trains, cars will be based on an immune cyber system. (Kaspersky,2018) ✓ All sectors, all functional departments and all brands are transformed to **be fully digital.** (Jungwirth, 2018)	✓ **Digital Mobile Maintenance** for manufacturing process: Nexeed Maintenance Support System **(Nexeed MSS) solution for** preventive and predictive ✓ Systematic **Production Improvement - Lean** ✓ **Intelligent Transport** Management: Milkrun driven by demand and **Driverless Transport** vehicles ✓ **Digital Shop Floor** Management: SIM with traceability ✓ **RFID in Logistics and IOT** ✓ Multi-product Line ✓ **3D Printing technology** ✓ **Human Robot Collaboration** ✓ Interactions M2M ✓ **Energy** Management (Bosch official site,2020)	✓ **Security and privacy** concerns regarding the IOT (Bosch official site,2020) ✓ **The cost** of implementation ✓ **Readiness** of the work force (Minturn,2020)	✓ Analyze and clarify the **requirements or objectives to achieve** ✓ Implement through **a step-by step** approach. ✓ **IoT Gateway** is a key aspect of Industry 4.0's functionality ✓ **Business's infrastructure** to support a wider scale of digitalization.
Schneider	✓ **Setting goals** that are outcomes focused ✓ **Smart -Industrial application** developer ecosystem ✓ **Connected devices** (products) ✓ **Digitization of Lean** manufacturing methods and tools (Arnó,2018)	✓ Robots and automation: **cobot, AGV** ✓ Machine-to-machine ✓ **Big Data** - Data centers ✓ Wireless sensors and **IOT** ✓ **Cloud** ✓ **Augmented reality:** EcoStruxure Augmented Operator Advisor ✓ **Artificial intelligence** for maintenance ✓ (Le Denn2019) and (Dieul,2015)	✓ Problematics **finding right technology solution** ✓ Lack of **implementation know-how** ✓ **Integration** of new technologies (Borgne,2020)	✓ Pervasive and **affordable communication** (Arnó,2018) ✓ **Openness and trust** in the digital platforms ✓ Offering not just technology solutions but also **business consultants** (Borgne,2020) ✓ Rigorous and **centralized program management** ✓ **External benchmarking** (Herweck ,2020)
Honeywell	✓ New business unit help manufacturers take advantage of the Industrial Internet of Things (IIoT).(Lock,2016) ✓ Building software that is rapidly moving Honeywell forward into new technology spaces, helping to serve customers. (Crimm,2019)	✓ **Cloud Computing & Cybersecurity** ✓ **IIoT** ✓ **Machine learning & Big Data** ✓ **Autonomous systems** ✓ **Machine to machine** (Honeywell official site,2020)	✓ Business complexity ✓ **Confusion** about which technology to use for what application. ✓ Lack on historical data and insights to apply to companies' analytics. (Dallara,2020)	✓ Constant operational support. ✓ Monitoring process from the technological supplier (Tapia,2018) ✓ Combine big data with industry knowledge and physical, empirical knowledge are critical. (Dallara,2020)
Ericsson	✓ **Empower an intelligent,** sustainable **and connected world** (Ekholm,2020) ✓ **Exploring the connectivity** (Ericsson official site, 2014). ✓ By 2020, 90% of the world's population is covered by mobile broadband networks.	✓ **Ericsson Cloud** Native Infrastructure solution ✓ **Smart Wireless devices for** Manufacturing ✓ **IoT Connectivity** (Josefsson, 2019)	✓ Deployment of **wireless networking** in a plant have been the main challenge. (Sabella,2018)	✓ **Consistency of technologies** with existing **values and past experiences**. Technology adoption becomes smoother (Sorlie, 2018) ✓ The key to smart manufacturing is **wireless connectivity** that enables mobility for connected devices. (Josefsson, 2019) ✓ Governmental policy is affecting the industrial market. (Sorlie, 2018)
General Electric	✓ Provide the users with **the real-time visibility and transparency** required. (Resnick,2020) ✓ **GE Digital** aims to transform the digital core, **power the industrial IOT,** and turn industrial insights into **accelerated returns.** (Daecher,2018)	✓ **Digital Tools** ✓ Predix Manufacturing ✓ **Data Cloud** ✓ Trackers and **IOT** ✓ **GE's Smart Helmet** (General Electric's official site, 2020)	✓ **Fear of displacement** of workers by machines. ✓ **Lack of knowledge** in technology by the workforce.(Schwab,2016) ✓ **Unreadiness** for the government **to achieve technology innovation** for public spaces. (Lye,2017)	✓ The **best approach** is the **one that fit best the specific circumstances** of each organization. (Daecher,2018) ✓ Strong foundation for **insights into operations** is critical step in journey to digital transformation. (Resnick,2020)
Latecoere	✓ 2017: Latécoère **officially laid the first stone of its 4.0 factory** in Toulouse-Montredon. ✓ Meeting industrial challenges and accelerate digitalization: **a digitalized, automated and connected factory.** ✓ 4.0 factory will combine **automation and innovative process**, by relying on **the Internet of things and cyber-physical systems.** (Latecoere,2017)	✓ **IOT** ✓ **Cyber-physical systems** ✓ **3D Printers** ✓ **Digital twins** ✓ **Automated and robotized** areas ✓ **RFID chips** for the tracking of **parts, equipment and tools** ✓ Automatization logistique (AGV) (Latecoere,2017)	✓ **Inefficient processes** may constitute a hindrance. ✓ Lack of communication: **intelligent collaboration** between the different production units and the factory ecosystem. (Latecoere,2017)	✓ **Lean is an enabler** to initiate **4.0.** ✓ Focus on **customer satisfaction**, by setting up **lean manufacturing lines (reducing** production times from a few weeks to a few days. (Latecoere,2017) ✓ **Get Labels** to increase visibility : Latecoere got "Window Industry of the future " by the Alliance Industrie du Futur (AIF). ✓ Label rewards **innovative production organization** based on **digital technologies,** and symbolizes the group commitment (Latecoere,2017)
Dassault	✓ **Virtual world** in the service of **real world** ✓ **Transparent work and access** the most **powerful 3D design, simulation, PLM, CAD,** manufacturing and innovation tools.(Dassault systems official site, 2020)	✓ **3D experience solutions, 3D printing** ✓ **Augmented reality Helmets** ✓ **Predictive maintenance** ✓ **Digital twin** ✓ **Digital tools:** CATIA, SIMULIA, EXALEAD (Dassault systems official site, 2020)	✓ Cost and Continuity Concerns ✓ Resistance to change ✓ Poor Data Quality ✓ Security Roadblocks ✓ Poor User Experience for Search Tools (Karin,2019)	✓ **Guarantee Lean Production** Assembly lines (called ARP) (Zouggar, 2020) ✓ **Empower the operators** ✓ Take benefits from **Data** ✓ New collaborative processes and architectural transformations to achieve excellence in integrated business operations. (Frost & Sullivan,2019)

One of the most common barriers that companies are dealing with is that sometimes the investment/cost for technologies is too high while benefits are not clear enough. For companies to land their objectives and vision into Industry 4.0, a first step is to choose a strategy according to their budget in such a way the solutions to adopt would fit better. Schwab (2016) reminds that practitioners are ready to commit in technologies if the Return On Investment is less than 3 years, otherwise difficulties rise. Scheer (2015) reveals the place of strategic plans with objectives of deploying the industry 4.0. The amount of the investment stands for the degree of complexity as well as the effort required in time. Disruptive innovations are often associated with high capital requirements and new business models design. Gradually various strategies regarding the budget and the effort can be ranged over a strategic scale.

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c. Future Main Research Axes

So far, many authors point out the lack of structured approach that combine LP and I4.0 (Rossini *et al.*, 2019; Santos *et al.*, 2021). Literature proposes separate and disconnected studies with fragmental introduction of technologies.

The research questions that arise are the following: *Beyond the link existing between Lean and technologies of Industry 4.0 (already documented in literature), how can we provide a roadmap guiding the managers in their understanding, visualizing, modeling of the links? How can we show the context influence and disclose the gradual implementation of technologies and Lean tools together?* Santos *et al.* (2021) emphasizes the necessity to build up a structured approach to deploy Industry 4.0 with or even with low level of Lean

Axes of research : Integrating Lean Production and Industry 4.0

Main axes	Future Challenges	Authors
Axis. 1 – Accurate study of cross analysis LP and I4.0	✓ Considering soft lean practices facilitating the implementation of I4.0	(Rosin.2020) (Bittencourt,2021)
	✓ Leading study of one-to-many analysis	(Salvadorinho,2021)
Axis.2 – Modeling the implementation of I4.0 and LP	✓ Identifying granularity and the level of the cross analysis I.40 and LM	(Rosin.2020) (Buer,2021)
	✓ New applications for I4.0 to support lean at control,optimisation and autonomy levels	(Najwa et al., 2022) (Tortorella,2021)
	✓ Modeling the impact of industry 4.0 technologies and LP on green production and sustainability.	(Dixit et al., 2022) (Touriki,2020)
	✓ Building new models of implementation of just I4.0 or combined I4.0 and LM model.	(Tiep,2020) (Langglotz,2021) (Dossou,2022) (Butt,2020)
Axis 3 – Performance evaluation and assessment of the efficiency	✓ Evaluation of the performance of combining I4.0 and LP	(Cifone,2021) (Buer,2020) (Mofolasayo et al., 2022) (Langglotz,2021)
	✓ Go beyond simple cross analysis and measure to which extent the performance is improved	(Ciano_2020) (Pereira,2019) (Majiwala,2020)
	✓ Empirical validation of synergies between lean and I4.0 and vice versa	(Santos et al., 2021) (Cifone,2021)

Although the number of publications on the subject has increased, proposing detailed models of the implementation of both methodologies is yet a big challenge (axis 1 in Table 3). The influence of soft Lean tools on the implementation of new technology needs to be investigated. Indeed, often Lean Production tools are considered as SMED, 5S, Visual Management, Jidoka, Heijunka, Takt Time, TPM, Kanban, ...however soft lean tools as standup meeting, A3, Kaizen are under-investigated, likely because of the difficulty of modeling social and managerial approaches. Moreover, the study of the interaction (one-to-many) instead of (one-to-one) seems highly recommended. Indeed, often studies show the influence of AGV on Kanban, the influence of Augmented reality in 5S, ... but how Kanban alone is able to influence many technologies or how one technology is prompted to sustain many Lean tools is yet evasive. Modeling the implementation of both LP and I4.0 technologies is the next axis of research (axis 2). Measuring the benefits seems to be interesting for performance evaluation and Return On Investment calculation (axis 3) and specially beyond the economic aspect. Many researchers are working considering the sustainability and ecofriendly tools for responsible introduction with sustainable green impact (Butt, 2020; Tortorella, 2021; Touriki, 2020; Dixit et al., 2022; Mofolasayo et al., 2022).

A gradual and step-by-step approach of Industry 4.0 implementation has been defended in this paper regarding the recommendations got from the benchmark (table 2) and outlines of Hofmann and Rüsch, 2017; Pereira et al., 2019; Rosin et al., 2020; Ciano et al., 2020 that remind the gap of existing works with neither explanation of the steps, constraints nor points of alert when implementing.

3. STRATEGIC METHODOLOGY

The target is to thoroughly study the combination between LP and I4.0 to monitor the impact on the industrial performance, at the level of a factory, an enterprise or even a supply chain. We browsed previously the existing studies subscribing to path 1 and path 2. The developed model will likely follow incremental steps to show gradually the choice of LP and I4.0 technology to implement according to indicators calculation.

The industrial reality demonstrated (through study cases, research papers and testimonies) that multiple possibilities exist with various connections between them. We have built a model with gradual and chronological steps (figure 2). It presents the global methodology and detailed section will describe all steps.

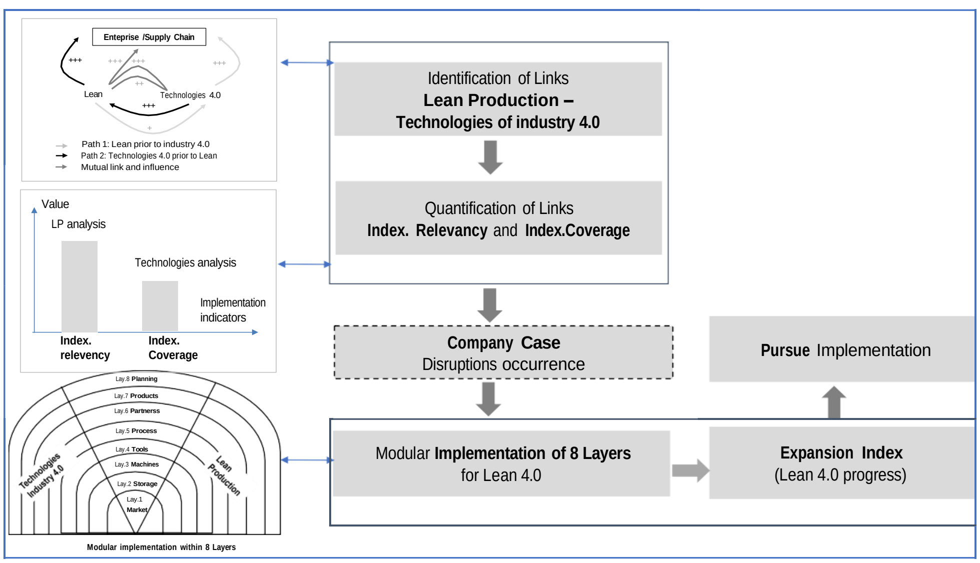

Figure 2. Methodology of linking LP and I4.0 technologies for common deployment

1. *Identification of the links* in cross combined analysis to know whether path 1, path 2 or both are considered. The identification of links and potential paths have to be studied in the same analysis to disclose the inter-influence. This step is a cornerstone to start the analysis of existing relations among a set of "Lean tools" and a set of "Technologies of industry 4.0". As a decision maker, this cross analysis increases the understanding of the possible connections.
2. *Quantification of key indexes for transformation: Relevancy index and Coverage index.* The obtained cross analysis is able to show the connections and interactions between LP and I4.0. Links are intended by the company but yet non-actionable decisions, devices, indicators exist in front of the choice of implementation. Which Lean tool to deploy in priority? Which Technology shall be implemented? What is the priority between them? If one tool is implemented, how does it impact technology and vice versa? Are so many questions to which the methodology is aiming to answer with its incremental deployment? The interest of Lean tools can be calculated regarding the Relevancy index. The more Lean Tool is increased in efficiency by technologies of I4.0, the more it is able to become prior. In the other side, the visualization of the interest of technology of I4.0 becomes possible thanks to the Coverage index. The more the Technology is supported by various Lean tools, the more the technology becomes consistent because of high value of coverage.
3. *Ranking of Relevancy index and Coverage index.* The ranking of priority is obtained for Lean tools and Technologies I4.0. The implementation can start gradually with the obtained ranking from the highest value to the lowest one. The implementation is advised to be *modular* within eight layers.
4. *Expansion index evaluation* to perceive the progress of implementation.

d. Identification of Links Between Lean and Industry 4.0

We base the choice of technologies regarding recent publications (Cardin, 2021; Dikhanbayera, 2021) and BCG Boston Consulting Group (Rubman et al., 2015) who already suggest a cartography with considered 9 pillars technologies of the era industry 4.0. We start by choosing the most recent industry 4.0 documents published to validate that selection. This proves that focusing on these technologies can give a bigger spectrum of the benefits combined with Lean.

A large study of literature leads to define the links between LP and I4.0 components. The figure 3 presents the results, arrows representing the influence. Although numerous references were consulted, it should be noted that not all articles use the same tools to represent the impact. Salvadorinho and Teixeira (2021) presents a matrix indicating with an "x" which I4.0 technologies have a contribution to Lean tools. Alternatively, Akkari and Valamede (2020) specify in a pie chart in more detail the correlation between both methodologies and their positive impact on the process due to this combination. Various papers conducting study cases prove the empowering effect of Lean combined with Industry 4.0. This allows practitioners to identify the benefits on specific industrial applications. Ciano *et al*. (2020) conducted a face-to-face survey to different industrial sectors that implemented digital tools together with Lean, and exposed the enabling effect in a table.

The way to represent these interactions is not only limited to tables and graphics like in Rosin *et al*., 2020; Salvadorinho and Teixeira, 2021. Buer *et al*. (2021), it developed a hierarchical multiple regression analysis, using operational performance as a dependent variable and including Lean and digitalization as predictor variables. The result of the study indicates that the digitalization only has a significant impact on operation performance when there is a high Lean implementation. In this part, we identify the link between technologies and Lean tools according to what we found in literature. The direction of arrows shows the meaning: Lean first and technology implemented after (↵), technology first and Lean used as support after (↥). The arrows show the influence, however, without a deeper modelling, the pattern of influence is yet evasive for decision makers who are in front of tricky situation. This identification alone is useless and let the manager with his questions: what to do with? and how to start? Our target is to quantify the link and build up potential strategic indicators to pursue the analysis of implementation and performance improvement over the time.

(1) Ghobakhloo,2019 (2) Ejsmont,2020 (3) Santos,2021 (4) Salvadorihno,2019 (5) Pagliosa,2019 (6) Ciano,2020 (7) Anosike et al., 2021 (8) Shanhin,2020 (9) Kolberg and Zühlke, 2015 (10) Valamede and Akkari, 2020 (11) Mrugalska and Wyrwicka, 2017 (12) Satoglu et al., 2018 (13) Mayr,2018 (14) Langlotz,2021 (15) Omogbai,2017 (16) Ayabakan,2019 (17) Rosin,2020 (18) Pereira,2019 (19) Zimmermann,2021 (20) Tortorella,2021 (21) Silvestri,2022 (22) Grajzova,2021 (23) Chiarini and Kumar, 2021 (24) Marinelli,2021 (25) Abd Rahman et al., 2020 (26) Afonso,2021

Figure 3. Influence links between LP and I4.0 technologies

We highlight that the figure 3 is not exhaustive nor limited, it shows the analytical approach and the symbol of representation to not confuse the nature of interactions. It can be enhanced, updated, completed and extended accordingly with the inclusion of new technologies or the consideration of other Lean tools.

1.1 Quantification of Links: Relevancy Index and Coverage Index

The purpose of this part is to formalize these influences by introducing two strategic key indexes: Relevancy and Coverage. Two hypotheses are addressed: Ha and Hb.

Ha: *Lean tool Li is supported by at least one Industry 4.0 technology Tj (Lean prior)* ***Hb:*** *Industry 4.0 technology Tj is supported by at least one Lean tool Li (Techno prior)* With:

Set (a): Set of Lean tools

Li: i^th^ Lean tool considered

Set (a)= {L1, …, Li | i=1…n} where n is the maximum number of Lean tools considered in the study

Set (b): Set of Industry 4.0 technologies

Tj: j^th^ Industry 4.0 technology considered

Set (b)= {T1, …, Tj | j= 1…m} where m is the maximum number of Industry 4.0 technologies considered in the study

The respective mathematical expressions for the hypotheses are: Ha: $\forall i$, $Li \in Set(a)$, $\exists\ Tjj \in Set(b) | Assig\ (i, jj)$: Li ⍰ Tj

Hb: $\forall jj, Tjj \in Set\ (b), \exists\ Li \in Set\ (a) | \ Assig\ (jj, i)$: Tj ⍰ Li

Where Assig (i,j): is the assignment variable. The assignment can either exist (=1) among two crossed analyses of Li and Tj or inexistent (=0). $Assig(i, jj) \in \{0,1\}$.

Lets define two indexes.

I.reli: Relevancy index of Lean tool i

$\forall i, Li \mid i = 1..n$, I.rel.i = $\sum n$

This index quantifies the relevancy for a Lean tool. If for the same Lean tool, many technologies contribute to improve the performance, the index discloses the relevance of the Lean tool to be combined with technologies and its role in increasing the performance.

I.covj: Coverage index of Industry 4.0 Technology j

$\forall jj, Tjj \mid jj = 1..m$, I.cov.j $=\sum m \ \ Assig\ (i, jj)$

This index quantifies the coverage for a Technology. If for the same Technology, many Lean tools contribute to improve the performance, the index discloses the strength of the technology and its suitability of deployment.

To get an overall estimation of the relevancy and coverage, we suggest to calculate the mean (μ), the average index regarding the total sample of Lean and total sample of technologies used in the study.

Relevancy Index: I.rel = μ(I.reli|i=1..n) = ⍰$\sum^n$

Coverage Index: I.cov = μ(I.covj| j=1..m) = ⍰$\sum^m$

m [$\sum$

jj=1

[$\sum^n$ $Assig(i, jj)$⍰/m]/n $Assig(jj, i)$⍰/n]/m

jj=1 i=1 i=1

The more the *Relevancy Index* and the *Coverage Index* are close to 100%, the more the adoption is interesting and the implementation prior to set up. When the *Relevancy Index* is close to 100%, the average contribution of Technology to support Lean is high and it shows that path 1 (Lean prior to Techno) is more likely to exist.

When the *Coverage Index* is close to 100%, the average contribution of Industry 4.0 technologies to support the Lean improvement is high. Table 4 shows the calculation of indexes per technology and per Lean tool.

Table 4 : Coverage and Relevancy indexes – results

Lean tools	JIT / Kanban	Poka-Yoke	SMED	VSM	5s	U cells	TPM / Jidoka	Heijunka / Takt time
Links number	10	8	6	8	8	2	10	6
Relevancy index (I.rel)	83%	67%	50%	67%	67%	17%	83%	50%

Industry 4.0 technologies	IIOT	Cloud comput.	Sensors	RFID	Big Data	AGVs	Robotics	AR / VR	Additive manufact.	Machine learning	Simulation	Digital twin
Links number	7	3	5	5	5	5	7	7	3	3	2	4
Coverage Index (I.cov)	88%	38%	63%	63%	63%	63%	88%	88%	38%	38%	25%	50%

Let's analyze a case of Industry 4.0 technology: *Internet of Things (IoT)*. Referring to figure 3, IoT is more likely to cover and support Kanban by enhancing the detectability of the cards in real time without waiting physical cards arrival. IoT is also more likely to detect the right reference in progress and avoid errors supporting poka yoke. IoT becomes a mean to support SMED since it allows to direct the right bins and the right tools detection in real time facilitating the setup times and decrease the time between references. Thanks to the transparency of the devices, their places and the time of transportation, IoT is able to reveal the time consumed for each operation without measuring them one by one. So, the drawing of the flow of VSM becomes possible and easier. Coverage Index of IoT seems high in this case.

(I.cov = 7). Then it can be considered that IoT is prior to implement because of its benefits and usefulness to ease the Lean.

For Additive Manufacturing, it can improve the just-in-time Lean approach through Kanban because it can guarantee to get the pieces and elements internally through internal 3D machines without waiting for purchasing order and delivery. It reduces the risk of shortages and ensure just-in-time. For instance, Dassault-Bordeaux has dedicated an internal unit of production (called "Fablab") to produce spare parts with 3D machines easy ready for the production line to sustain the just-in-time concept. Also, Additive Manufacturing can reduce errors thanks to the easiness to print in 3D many technical poka yoke to ensure error proofing and ensure the quality at the origin of the process. SMED is aiming to reduce the setup times, with the help of Additive Manufacturing, it becomes easier to get materials, devices in front of line of production to reduce the times of changeover. However, we can perceive that Additive Manufacturing has no link with VSM, 5S and Ucells, so its coverage index is equal I.cov = 4. When the company has to choose and does hesitate among IoT and 3D, this evaluation provides index of coverage that assist decision maker: IoT prior to 3D.

The I.rel (PokaYoke) = 7 and Ucells (2). This evaluation shows to which extent a Lean tool perform in a production system. The more the Relevancy index is high, the more likely the Lean tool is improved by technologies. For instance, if a manager would like to assess JIT relevancy (83%) this index uncovers to which extent this Lean tool is useful for operational performance and the probability of being augmented with technologies. JIT seems to be more relevant to implement then Ucell which can be augmented but not so much (17%). This first quantitative assessment allows a graduation of priority for implementation of Lean tools.

e. *Modular Implementation of Industry 4.0: Eight layers*

Once the *I.rel and I.cov* indexes estimated, a scalable list of Lean tools and Technologies becomes possible to visualize for the managers. The quantification of the influence provides a possible ranking of the technologies and the Lean tools to perceive those prior to be implemented.

We argue the possibility to classify them to support the managers. Beside the calculation of indexes, it is important to perceive the requirements of the companies and their readiness to implement new technologies. Indeed, many companies transition the era of industry 4.0 through the problems that they meet in daily life (outcomes of Gemba: Where the value is created in the field and shop floors). In this direction, this part suggests a modular and practical aspect of industry 4.0 implementation.

We would like to make possible for any company to position itself in this cartography to use "plug and play" approach. It becomes possible to implement gradually regarding the priority given in its business plan over the coming years and support the decision makers in their strategic choice and deployment of technologies accordingly with the layer they are concerned by.

When analyzing a sample of 84 documents in our databases (theoretical industrial study cases, collaborations of our research center with industrials, internal documentations, public materials, company cases (Table 2) and scientific papers about industrial dysfunctions, an evidence comes out that we try to categorize. The outcomes of this analysis highlight various possibilities of technologies implementation and outline the notion of "granularity" that depends on the aspect the company is interested by and the position in the company hierarchy. The idea of Layers emerges to structure and point out the various aspects that companies can be interested by independently. Eight layers have been identified in the analysis

(Figure 4).

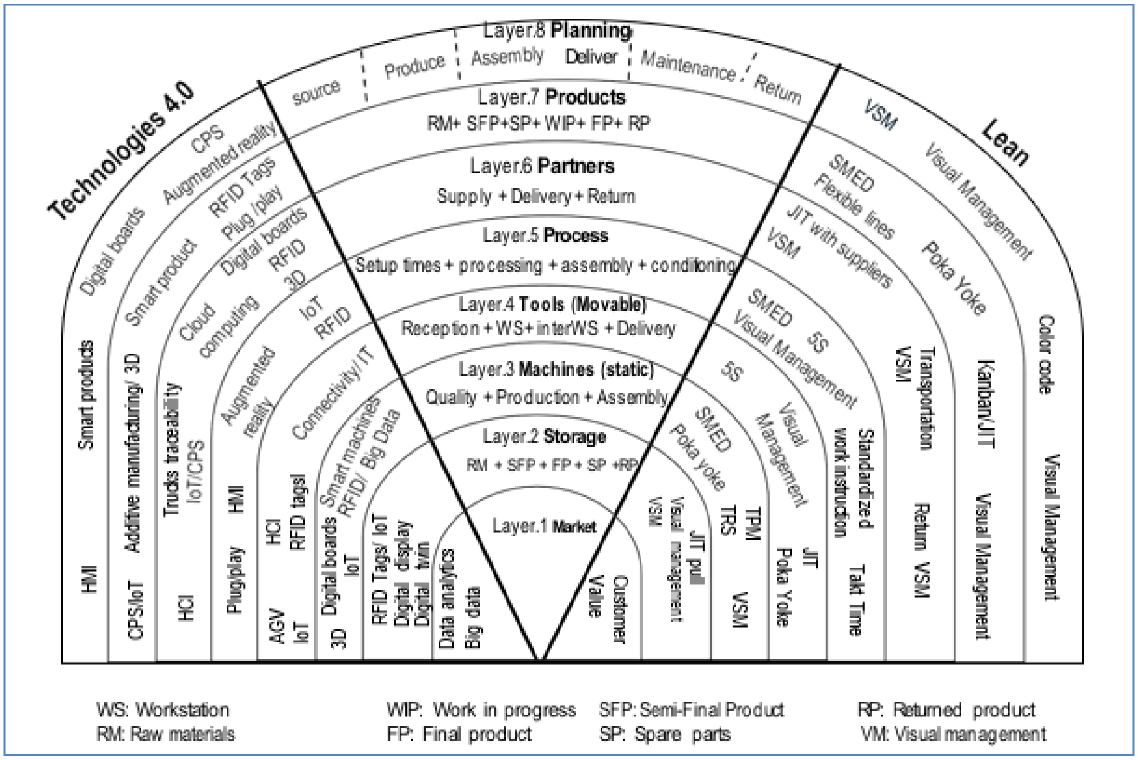

Figure 4. Modular implementation of industry 4.0 Through Layers

Each layer represents the aspect to consider in the strategy of the company. *Market, Storage, Machines, Tools, Process, Partners, Products, Planning* are such many aspects where disruptions rise.

In this methodology, each company has the challenge to analyze different layers and disclose those deserving deeper attention.

The companies that are young in the transformation may consider one or two layers. Others can be considered as very advanced in technological transformation of industry 4.0 if they achieve 6-8 layers. The target is not to get them all but to help managers to impulse the transformation and position themselves to implement relevantly, gradually and at the good moment.

Let's detail the interest of implementing industry 4.0 with layers concept.

Set (l): Set of layers

αk: k^th layer

Set (l)= {α1, …, α8}

We argue that the found Li and Tj previously can be considered in each layer. To choose the one adapted, I.cov and I.rel seems worth to analyse. The manager can keep the Li and Tj that records high I.cov and I.rel.

Let's consider Hc: *Whatever the layer concerned, there will be always a technology with high index of coverage and a lean tool with high level of relevancy suitable to use for supporting the efficiency of the layer* (subsequently performance of the company).

Hc: $\forall k \mid \alpha k \in Set\ (ll)$, ∃ Li ∈ $Set\ (a)\ anaa$ ∃ Tj ∈ $Set\ (b)$ | <Li |I.rel(High)> and Ij| I.cov(High)>

The gradual implementation takes the following form: if a company is interested only by forecast improvement because disruption comes out from market disturbance, α = 1. It means that the first layer is prior and deserves analysis about the suitable technologies and Lean with high relevancy index. If the company considers warehouse as prior layer, it starts leading its analysis. Hence, the company gradually extends the analysis to other layers from 1 to 8.

By the way, as mentioned in the Figure 4, it becomes possible, over the unfolding of industry 4.0 project, to measure the *Expansion index.*

Expansion Index: I.exp = $\sum_{k=1}^{8} \alpha k$ /8. The ultimate target would be to get a 100% expansion index for all layers covered by the analysis. The company can settle gradual targets to achieve them step by step. This expansion measure is a useful indicator to disclose the state of maturity level regarding lean 4.0 progress. If the index is low it means many new projects and improvements have to be led to browse a maximum layer. If the index is increasingly high, the company case is becoming more and more mature regarding combined implementation of Lean and I4.0 committing in gradual successful Lean 4.0.

5. DISCUSSION

The methodology that we suggest is structured in different steps and aims at calculating relevancy and coverage indexes with gradual and incremental implementation through different layers for the monitoring of the expansion index. It is important for managers to know how to proceed and how to start implementation and overcome the recurrent dilemma to which they are confronted: How to start with LP and I4.0 technologies? What to implement? What is the mutual influence between LP and I4.0 technologies? We suggest an incremental methodology moving through: *analysis of matrix of links – visualization of indexes of relevancy and coverage – positioning in the layers and evaluation of expansion index*. The Layers are split into: *Market, Machines, Tools, Process, Products, Partners and Planning*

.

Regarding the priority unveiled by the indexes and the disruptions experienced by the company, the managers may choose one layer and gradually implement others till covering the whole system. Expansion index can be measured, it allows to monitor and follow the progress of implementation and deployment. At each layer considered, the technologies with high *coverage index* and lean tools with high *relevancy index* will be selected to test the impact and increase the efficiency. For instance, a company having stable demand and regular order book can judge that *market layer* is not a priority, consequently committing in implementing the technology of “Data analytics” or machine learning would be a non-sense. Nevertheless, if the company is confronted to warehouses problems, it will direct its attention to the layer “storages” that is often a big issue in industrial reality because of the lock up of funds and damage risks for raw materials, finished products and semi-final products. In this case, embracing era of industry 4.0 may start with technologies targeting solving the issue of “storage” through deployment of digital display, RFID Tags, IoT to evolve concomitantly with Just In time, Kanban, visual management and bottleneck identification through VSM (Figure 4).

The figure 4 shows technologies potentially supporting the Lean tools used at each layer. Other companies will judge layer of “partners” as crucial because of the supply chain strategic context and the necessity to manage the network interactions. In this layer dealing with “partners”, the JIT notion of Lean is essential to build up with suppliers for reliable supply chain. The technologies associated with can be trucks traceability, cloud computing, RFID, IoT and CPS in general, it can constitute the sub-categories to analyze and ranked with I.rel and I.cov for adequate implementation. The aim of deployment by layers is to provide visual cartography of possible modular implementation to support managers and practitioners with a decision-aided method. Each company may choose its layers according to its Gemba and field issues, followed by analysis of links and I.cov and I.rel evaluation to progress in the implementation through the expansion index.

The algorithm in Figure.5 summarizes the developed methodology combining Lean production and Technologies of Industry 4.0.

1 – Business Plan: (a) Strategy of Lean deployement
(b) Strategy of Technologies

2 – Building matrix of links : n x m

3 – Quantifying the links

Ha, Hb, Set (a): Lean tools, Set (b): Technologies of I4.0

Set (a)= $\{L_1,\dots, Li \mid i=1..n\}$

Set (b)= $\{T_1,\dots, T_j \mid j= 1..m\}$

H_a: $\forall i, Li \in Set(a), \exists Ijj \in Set(b) \mid Assig(i,jj) : L_i \leftarrow T_j$

H_b: $\forall jj, Tjj \in Set(b), \exists Li \in Set(a) \mid Assig(jj,i)\ T_j \leftarrow L_i$

I.rel$_i$: Relevancy index of Lean tool i

$\forall i, Li \mid i = 1..n$, $I.rel._i = \left[\sum_{jj=1}^{m} Assig(i,jj)\right]$

I.cov$_j$: Coverage index of Industry 4.0 Technology j

$\forall jj, Tjj \mid jj = 1..m$, $I.cov._j = \left[\sum_{i=1}^{n} Assig(jj,i)\right]$

Relevancy

$\mu_{(I.reli|i=1..n)} = \left[\sum_{i=1}^{n}[[\sum_{jj=1}^{m} Assig(i,jj)\right]$

Coverage

$\mu_{(I.covj|\ j=1..m)} = \left[\sum_{jj=1}^{m}[[\sum_{i=1}^{n} Assig(jj,i)\right]$

4 – Deployment per layer

Set (l): Set of layers

α_k: k^{th} layer

Set (l)= $\{\alpha_1,\dots,\alpha_8\}$

H_c: $\forall k \mid \alpha_k \in Set(l), , \exists L_i \in Set(a)\ anaa\ \exists T_j \in Set(b) \mid$

$<L_i \mid I._{relev}(High)>$ and $I_j \mid I._{cov}(High)>$

Expansion Index: $I._{exp} = \sum_{k=1}^{8}(\alpha_k)/8$

5 – Monitoring indexes to progress gradually

Figure 5. Algorithm of the strategic methodology

This research work is framed by assigned hypothesis and presents some limitations that should be evoked. The methodology developed concerns some Lean tools in the set S(a) and a number of technologies emerging in industry 4.0 in set S(b). No exhaustivity can be claimed because the technologies of industry 4.0 are evolving and new one can get interest and included in the model (edge computing, blockchain, …), the same argument for Lean tools that can be extended to the soft lean tools hardly modelled however theoretically possible to include (A3 analysis, stand up meeting, Obeya, Kaizen, …). Another aspect is the *step-by-step* implementation. The target in the future would be to automatize the method to achieve quick evaluation of indexes and efficient assistance to managers for their business plan. Automatic indexes calculation through a dedicated platform for decision aided progress would be helpful based on the algorithm shown above.
Also, multiple cases applications to get feedbacks for validating the usefulness and the operational use of the method would be led in near future.

4. CONCLUSION

Lean and industry 4.0 technologies have increasingly gained interest during this last decade. This paper suggests an attempt of strategic analysis to go beyond simple cross combined analysis as often done. To reposition the target of this contribution, we remind the main issues that companies are tackled to: How to implement Lean? How to lead Industry 4.0 transformation? Are they able to lead both concomitantly with a roadmap of influence? Likely very few of them would feel comfortable to answer "yes". To ease the analysis steps of the managerial staff from a strategic point of view, we suggest a methodology with incremental plug-and-play possibilities. Once the table of influence established, it is worth to go deeper to understand the way the inter-relations can influence the decision of industry 4.0 deployment. The different steps of the methodology outline the content of the analysis, the calculation procedure and the outcomes use for ranking as Index of relevancy and Index of coverage. An implementation representation based on eight layers eases the decisions to direct managers to fulfil gradual implementation with visual possibilities. Roche (2013), from Thales Group (providing aeronautic/avionic systems), leads Lean transformation over various sites, reminds accurately that "we can solve better what we can perceive". In this sense, we tried to develop a methodology able to progress step-by-step (e.g: Schneider) with plug-and-play approach (e.g: Dassault) ensuring Test and Learn possibilities (e.g: Faurecia). The interest of this

methodology is the gain of time given to managers. Indeed, when previously the practitioners were using Test and Learn approach evolving by steps (inducing loss of times and missing earnings when the technology implemented does not fit), today we can hope contribute throughout this methodology to the clarification of the context (necessity of Lean and/or Technologies of industry 4.0 deployment), visualization of the interactions (table of links with arrows representation), evaluation of the challenges and priorities (I.rel and I.cov), frame of the implementation regarding the layers identification and, finally, estimation using the expansion index to follow and monitor the control and the implementation of LP and I4.0 technologies. In near future, an application of this methodology will be led in association with companies of the French "Nouvelle Aquitaine" region. The companies of this region have beneficiated from the "Factory of the future" regional plan since 2014 which is still pursued. The future work will target to push a survey to get back the appreciation of the managers from the field of Lean and I4.0. Moreover, technically the target is to automatize the pre-selection of initial data, parameters of contexts and trigger combined analysis to carry out the strategic framework automatically.

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