



Lean European Action-learning Network utilising Industry 4.0

## WP 7 – Reference Model for Smart Lean Operations

D7.1 Reference model for Smart Lean Operations

D7.2 Implementation process for Smart Lean Operations

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*“We need operations managers able to link opportunities of Industry 4.0 with Lean techniques, methods and philosophy to improve business processes”*, Erlend Alfnes, project leader of the LEAN 4.0 project.

**LEAN 4.0 Version Control Table**

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## 1 Introduction

### 1.1 LEAN 4.0

LEAN 4.0 is a collaborative initiative between four leading Higher Education Institutions (HEI) and four industrial enterprises that aims to integrate Industry 4.0 smart technologies within the proven Lean Manufacturing paradigm in order to improve factory performances. Besides the necessity of this integration to face in an efficient and effective way the continuous market changes and needs, knowledges and experiences regarding both the continuous improvement activities associated with Lean Manufacturing and the disruptive technological innovations of Industry 4.0 are still lacking.

Together, the partners of LEAN 4.0 will address this significant gap in knowledge and practical experience, anticipating the European manufacturing industry's contemporary need for development of new skills for the operations management brought along by "Industry 4.0". By acting as a conceptual framework, LEAN 4.0 will inspire the operation managers of the future and will prepare European Manufacturing for the challenges that lie ahead.

### 1.2 Work Package 7 – Reference Model for Smart Lean Operations

The adoption of Smart Lean Operations is crucial for a company since, through their adoption, a company can maximize its performance by becoming a so called LEAN4.0 company. However, their adoption is often challenging, and Work Package 7 aims to support the adoption of Smart Lean Operations by conceptualizing and developing a reference model for Smart Lean Operations. Specifically, the reference model, building upon the knowledge and experiences about practices gained in the development of WP1, WP3, WP4, and WP6, provides a tool for designing and implementing Smart Lean Operations in European industries. Specifically, the development of the reference model for Smart Lean Operations is covered in Deliverable 7.1 (i.e. Reference model for Smart Lean Operations), while the implementation process for Smart Lean Operations is covered in Deliverable 7.2 (i.e. Implementation process for Smart Lean Operations), that will both be discussed in the following.

### 1.3 Deliverable D7.1 - Reference model for Smart Lean Operations

Deliverable D7.1 of Work Package 7 concerns the development and formalization of a reference model for Smart Lean Operations. After having identified the different stages a company has to go through in its development towards a LEAN4.0 company, the reference model provides a tool that can assist managers in their goal to develop their company into a LEAN4.0 company. Specifically, first the reference model allows managers to map the current LEAN4.0 status of their companies and to assess their position with respect to the final goal (that is the LEAN4.0 company). Then, the reference model provides a set of best practices for Smart Lean Operations that can support the development of a company towards a LEAN4.0 company. Moreover, at the end of this Deliverable, ongoing trends towards the achievement of the LEAN4.0 dimension for a company identified from some of the pilot projects carried out in WP6 and from interviews with managers will be reported.

### 1.4 Deliverable D7.2 - Implementation process for Smart Lean Operations

Deliverable D7.2 of Work Package 2 deals with the standard implementation process for Smart Lean operations in order to achieve the final company goal of a LEAN4.0 dimension. Specifically, building upon the results of D7.1, of WP3 (i.e. the BNAL methodology) and of WP6 (i.e. the pilot projects), the implementation process (i) defines the different phases and

decision gates characterizing the company's development process towards the LEAN4.0 dimension, (ii) supports a maturity evaluation at each decision gate and (iii) design guidelines for each decision gate.

## 2 D7.1 - Reference model for Smart Lean Operations

### 2.1 Introduction

As discussed before, the purpose of Deliverable D7.1 is to develop and formalize a reference model for Smart Lean Operations that builds upon the knowledges and experiences gained during the development of WP1, WP4 and WP6. A reference model for Smart Lean Operations can be seen as a guide for managers who wants to develop their company towards a LEAN4.0 company, where Industry 4.0 (I4.0) technologies and the proven Lean Manufacturing paradigm are efficiently and successfully integrated in order to maximize the company's performances. Specifically, a company can decide to take a LEAN4.0 journey for solving the root cause of a particular problem (technology pull) or just because of the availability or offering of new technology (technology push). Strategic alignment, however, is always needed, and the reference model herein developed serves this viewpoint. It is worth mentioning that, based on the scope of our project, the reference model herein developed is valid only for high variety-low volume industries, and using it in a different environment (e.g. low variety-high volume industries) might not lead to any benefit<sup>1</sup>.

In order to develop their companies towards the final goal of the LEAN4.0 dimension, managers have first (Step 1) to map the current status (or maturity level) of their companies in terms of Lean and I4.0 technologies. In this way, managers can understand which is the current situation of their company, as well as think about the LEAN4.0 development of their companies. Specifically, in this phase, it is important to root the LEAN4.0 journey in 'the Gemba', where the project outcome will have an impact. It is in fact important to study the current performance and way of working at the beginning of the LEAN4.0 journey. It is also important in this initial stage of developing a LEAN4.0 project to involve employees who spend their time at the Gemba. This 'Gemba study' provides additional information about the relevance and the feasibility of a possible LEAN4.0 project. This helps the company and the operations manager to make choices in the projects to be carried out.

After this step, managers have then (Step 2) to understand how they can move closer to the final goal of having a LEAN4.0 company. Specifically, they need to know which combination of Lean practices and I4.0 technologies can be beneficial in achieving their goal.

The reference model has hence to consider these two steps and to support managers in carrying out them. Specifically, we will see in the following how the taxonomy developed in Deliverable 1.2 can support Step 1 and how the combination of this taxonomy with the best practices for Smart Lean Operations resulting from WP4 can support Step 2.

Moreover, at the end of D7.1, we will report which are the ongoing trends towards the achievement of the LEAN4.0 dimension that we have identified from some of the pilot projects

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<sup>1</sup> As an example, certain Lean practices that are efficient in a high variety-low volume environment are not similarly efficient in a low variety-high volume environment (e.g. Heijunka).



carried out in WP6 and from interviews with managers. This will serve as starting point for D7.2.

## 2.2 LEAN4.0 maturity level

The first part of the reference model has to deal with the determination of the LEAN4.0 maturity level of a company. To do so, managers have to map the current status (or maturity level) of their companies, determining (1) the extent to which Lean improvement is embedded in their organization, and (2) the extent to which Industry 4.0 technologies are adopted to serve the road towards perfection, and to do so they can leverage the taxonomy developed in D1.2 (A taxonomy of smart Lean operations). In this phase, it is important to root the LEAN4.0 journey in ‘the Gemba’, where the project outcome will have an impact. It is in fact important to study the current performance and way of working at the beginning of the LEAN4.0 journey. It is also important in this initial stage of developing a LEAN4.0 project to involve employees who spend their time at the Gemba. This ‘Gemba study’ provides additional information about the relevance and the feasibility of a possible LEAN4.0 project. This helps the company and the operations manager to make choices in the projects to be carried out.

Starting with the Lean improvement status, based on the work of Bessant et al. (2001), in D1.2 we have identified four maturity stages, i.e. “*Ad Hoc*”, “*Structured and Dedicated*”, “*Strategically Linked*”, and “*Autonomous and Self-Learning*”, that will be discussed in details in the following. Each maturity stage indicates to what extent companies have integrated Lean in the DNA of their workers and organization.

- Ad Hoc: usually one of the managers (many times the production manager) is enthusiastic about Lean, and develops Lean in his own department, involving “his/her” employees, and improvement projects are limited only to this department.
- Structured and Dedicated: here there is a cooperation between the departments and inter-department improvement projects take place. These improvement projects are setup in a structured and dedicated way. There are probably improvement boards, a suggestion box, and such. The start of these improvements, however, is not based on the strategy of the company, but more on the problems discovered in practice.
- Strategically Linked: there is policy deployment, and improvements are linked to the strategy of the company. There is no sub-optimization anymore.
- Autonomous and Self-Learning: improvement is a routine performed by the whole organization. Improvement initiatives are not dependent on top management but comes from the communication between the several organizational levels and department. The company applies Hoshin Kanri in a structured manner, including catch ball principles.

Dealing with the Industry 4.0 maturity level, then, similarly to what done by Tao and Zhang (2017), in D1.2 we have identified four main maturity stages as well, i.e. “*Computerization*”, “*Connectivity*”, “*Visibility and Traceability*”, and “*Self-Learning and Predictive Power*”.

- Computerization: computers are used just for their main functions (e.g. CAD, CAPP, ERP) in order to gain information.
- Connectivity: connectivity between the various applications and between the various information available
- Visibility and Traceability: well-performing link of information systems with the actual status and locations of products and resources.

- Self-Learning and Predictive Power: all the data are used to continuously improve the whole system in an automated and self-learning way

After having mapped the current status of their companies, managers can place them in the taxonomy matrix developed in D1.2 and herein reported in Figure 1.

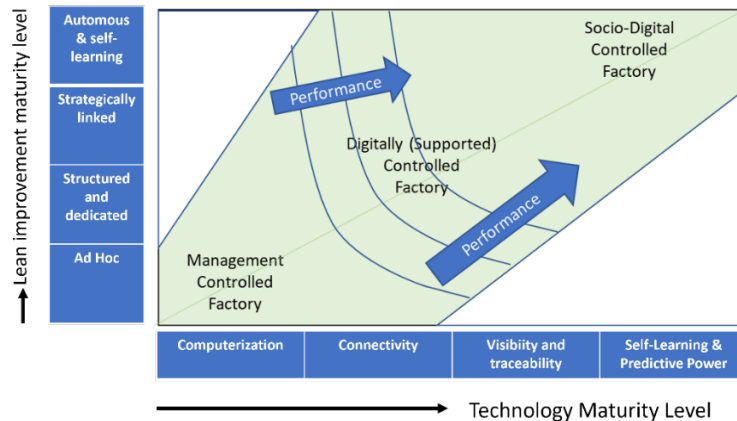


Figure 1. Taxonomy matrix of Lean improvement and Industry 4.0 development maturity level

Depending on the position of their companies, managers can determine whether their companies can be considered a “*Management Controlled Factory*”, a “*Digitally (Supported) Controlled Factory*”, or a “*Socio Digital Controlled Factory*” (which will be described in the following) or in transition towards the last two. Before describing these three main type of companies, it is worth mentioning that this distinction is inspired by various industrial cases and surveys, and managers recognize their companies in this distinction (Slomp et al., 2020). In particular, managers recognize the impossibility to place themselves in the white areas. From the surveys done for developing the taxonomy (see D.1.2) it emerged that using Lean principles needs the support of administrative technologies (i.e. the level of computerization) and that further levels in the use of Lean improvement can be realized only with connectivity, while using advanced levels of technology ask for advanced levels of the use of Lean principles (there are hence no companies that use advanced technology without attention for Lean principles).

We will now describe the three main type of companies:

- **Management Controlled Factory:** Information systems have limited functionality, and they are not connected (it corresponds basically to the Industry 2.0 era). Management spends substantial time on firefighting. The company is functionally organized and improvements come from the management.
- **Digitally (Supported) Controlled Factory:** Information systems have a good functionality and they are to a certain extent connected. However, the information exchange with the shop floor is limited, with no real time data for example, and management experiences a gap between information coming from the systems and reality (it corresponds basically to the Industry 3.0 era, but some I4.0 technologies are also present). Improvements are local and companies are moving towards (semi) autonomous improvement teams.
- **Socio Digital Controlled Factory:** Management focuses on realizing an agile factory. Information systems are fully connected and information is available everywhere, with no gap between information and reality (it corresponds basically to the Industry 4.0

era). Improvements are local as well as cross-departmental and focused on improving value streams, with semi-autonomous teams that are fully responsible for parts of the value streams. Intelligent software is used for the coordination between the teams and for their links to suppliers and (external) customers.

The final goal of managers is hence that of developing their companies from their current status towards a Socio Digital Controlled Factory (or, as we call it before, a LEAN4.0 company). As briefly discussed before, this represents the factory of the future, where the social aspect is crucial, and respect and teamwork are key elements of this social system. The social system furthermore performs well if there is a ‘growth mindset’ where related challenges are dealt with by means of kaizen (PDCA) and by understanding that decisions should not be made without a deep understanding where things have to be done. This is nicely depicted in the model of ‘Toyota Way 2001’ (Figure 2).

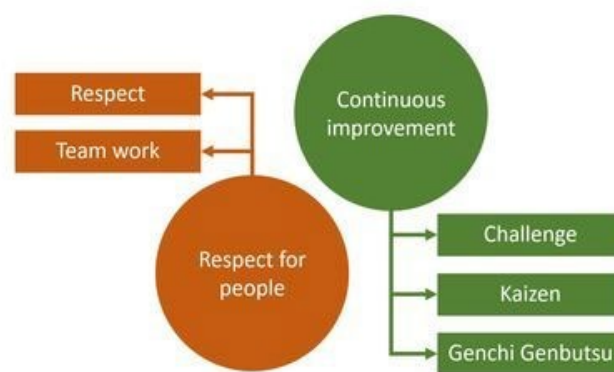


Figure 2. Toyota Way 2001, picture from <https://www.wevalgo.com/know-how/lean-management/lean-manufacturing>

Moreover, the factory of the future is also a digital factory where information is everywhere available and can be used to gain a world-class company. Figure 3 gives a general, schematic, idea of architecture of the digital factory: all information systems in the company are connected, the status of orders (products) is accurate and in real-time available as well as the status of resources (machines and people), workers are supported by technologies, for making decisions as well as for supporting them in their executive work, and activities are coordinated both horizontally and vertically.

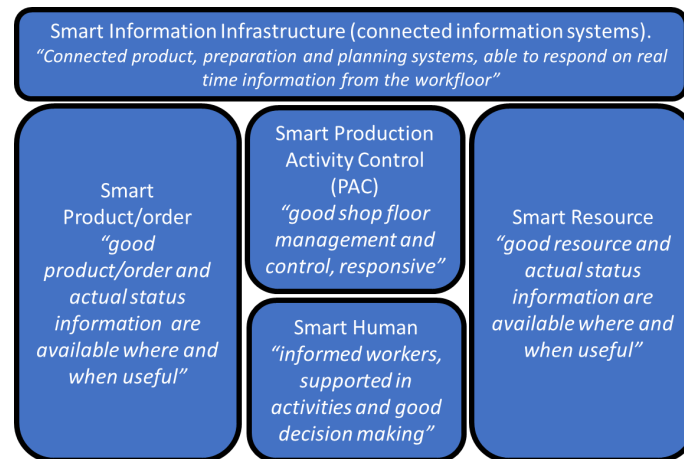


Figure 3. The architecture of the digital factory (inspired by Yoon et al. (2012))

In the next Section and in the Section related to D7.2 we will see how managers try to transform their companies into a Socio Digital Controlled Factory.

### 2.3 Towards a LEAN4.0 company: the enabling Smart Lean Operations

In this section we will see how managers can develop their companies into a “Socio Digital Controlled Factory” (in the following, “Socio Digital Controlled Factory” will be used as synonymous of the “LEAN4.0 company” used before). To do so, managers need to understand which combinations of Lean practices and I4.0 technologies (i.e. Smart Lean Operations) allow them to achieve their goal. Therefore, to support managers in their development towards a LEAN4.0 dimension for their companies, in the following we will link the best practices for Smart Lean Operations identified in WP4 with the types of companies identifiable from the taxonomy. Specifically, due to the low (basically null) level of Lean practices and null level of I4.0 technologies present in the “Management Controlled Factory”, the Smart Lean identified in WP4 can be encountered only in the “Digitally (Supported) Controlled Factory” and, above all, in the “Socio Digital Controlled Factory”, and therefore we limit our analysis only to these two. The “Management Controlled Factory” can be considered a starting point: Lean practices and I4.0 technologies (especially the latter) are not in place here, and managers need to understand which are the Smart Lean Operations that allow them to develop their company first into a “Digitally (Supported) Controlled Factory”, and then into the final goal of a “Socio Digital Controlled Factory”.

Before doing that, however, it is probably useful to report the main Lean practices and I4.0 technologies identified in WP4 and that will be considered in the following (Table 1).

Lean practices		Industry 4.0 technologies	
Lean practice	Description	I4.0 technology	Description
Continuous flow	It aims to move in the shortest time a single product through every step of the process instead of grouping work items into batches	Sensors & Actuators	Sensors are devices that aim to detect events or changes and to send the information to Actuators (component of a machine responsible for moving & controlling a mechanism/system)
Pull	It is the technique of planning the production according to the customer's request: every subsequent operation has to initiate the operation of its predecessor	Cloud computing	Serve to store the high amount of data generated that can be accessed from anywhere
Single Minute Exchange of Die (SMED)	It enables smaller batches and shorter lead times by drastically reducing changeover times	Big Data (and Data Analytics)	Fast analysis through Data Analytics of the huge amount of data generated by sensors and control systems (Big Data) to take fast decision
Total Productive Maintenance (TPM)	It aims to avoid failure of machines and equipment through periodical maintenance procedures and to maintain low rectification time in case of failure	Integrative technologies	Technologies that allow to integrate the information systems of the whole value chain
Jidoka	It aims to ensure that anomalies are detected during processes and not sent to the next station	Assistive technologies	Any technology assisting the operator in operational/decision making activities (AR, VR, cobot, ...)
Six Sigma	It seeks to improve the quality of the output of a process by identifying and removing the causes of defects and minimizing impact variability in manufacturing processes	Decision support systems	Technologies that intends to improve the creation and planning of working procedures (simulation, digital twin, ...)
Customer involvement	It consists of the connectedness to the customer base and predicting changes in market trends	Advanced algorithm	Algorithms that improve automatically through experience aiming to maximize the chances of successfully achieving a certain goal
Supplier integration	It allows suppliers to be regularly informed about the status and condition of the products and services provided by them	Additive Manufacturing	It is an additive process of forming objects, layer upon layer from data and 3D models
Kaizen	It represents the continuous improvement concept, that aims to improve the production and produce profits through cost reduction by eliminating waste	Advanced Vehicles	Vehicles that do not require a human operator to be driving (AGV, AMR) and/or that can follow innovative pathways (drones)
People & teamwork	It aims to achieve a combination of many people in small groups working together, and this is fundamental to ensure the expected outcomes of a company		

Table 1. Summary of the Lean practices and I4.0 technologies identified in WP4

After this overview of the Lean practices and I4.0 technologies identified in WP4, we can now see which of their combinations fit into the two different types of companies identifiable from the taxonomy that are relevant for us, i.e. “Digitally (Supported) Controlled Factory” and “Socio Digital Controlled Factory”.

### ***Digitally (Supported) Controlled Factory***

In this type of company, (i) information systems have a good functionality and they are to a certain extent connected, but (ii) the information exchange with the shop floor is limited (no real-time data for example). Moreover, improvements are local, and companies are moving towards (semi-) autonomous improvement teams.

Here some main Lean practices are adopted, but they are limitedly integrated with technologies. In this type of companies, the Lean practices of Continuous flow, Pull, SMED, TPM, Jidoka, Six Sigma and Kaizen are used, but they are not exploited to their full potentials since technologies are not used/fully exploited. For example, in “Digitally (Supported) Controlled Factory”, TPM is adopted in the form of preventive maintenance, while it is not possible to carry out predictive maintenance since no real-time information is available.

In “Digitally (Supported) Controlled Factory” we can find the following combinations of Lean practices and I4.0 technologies reported in WP4, and the papers discussing them are reported for more details:

1. Continuous flow & Assistive technologies
  - a. Augmented Reality (AR) can provide information to operators about cycle time and tasks to perform, hence supporting Just in Time production (Kolberg and Zühlke, 2015; Valamede and Santos Akkari, 2020)
  - b. Virtual Reality (VR) can be used to assembly training, resulting in fewer errors and lesser time in actual product assembly when compared to the traditional training group (Abidi et al., 2019)
  - c. Cobots can collaborate with employees in assembly operations for instance (Fast-Berglund et al., 2016; Levratti et al., 2019)
2. Continuous flow & Additive manufacturing
  - a. Additive Manufacturing (AM) allows to achieve a one-piece flow production thanks to the print-on-demand production system (Chen and Lin, 2017)
3. Continuous flow & Advanced Vehicles
  - a. AGV and AMR can transport single units through a flexible material flow (Giuseppe Fragapane et al., 2020; Powell et al., 2018)
  - b. Continuous flow is guaranteed by the capability of AMR to avoid/reduce congestion by rerouting the vehicle to an alternative path in case of obstacles (Giuseppe Fragapane et al., 2020)
4. Pull & Additive manufacturing
  - a. AM promotes pull through the elimination of inventory due to the print-on-demand production system achievable (Chen and Lin, 2017)
5. SMED & Assistive technologies
  - a. AR allows the visualization of each step of the changeover process (Brunet-Thornton and Martinez, n.d.)
6. SMED & Decision support systems

- a. Optimization of machine setups testing various methods through simulations (Rüßmann et al., n.d.)
- 7. SMED & Additive manufacturing
  - a. AM allows to omit times for selection, search and adjustment of tools and workpieces (no setup time and no requirement for tooling due to the layer-by-layer manufacturing technique) (WANG et al., 2016)
- 8. TPM & Additive Manufacturing
  - a. If a failure demands a part to be replaced, the new spare part can be printed using Additive Manufacturing (Sanders et al., 2017)
- 9. TPM & Assistive Technologies
  - a. AR and VR facilitate the learning and training of the operators (Hold et al., 2017; Li et al., 2003; Palmarini et al., 2018; Webel et al., 2013)
  - b. AR allows to interact with maintenance experts: by displaying virtual elements, operators can be guided remotely (Zhang et al., 2015; Zhu et al., 2012)
- 10. Jidoka & Assistive Technologies
  - a. AR allows error-free picking and assembly providing instructions to the operators (Grajewski et al., 2013; Ong et al., 2008; Park et al., 2014; Reif et al., 2010; Wang et al., 2013; Zhang et al., 2011)
- 11. Jidoka & Assistive Technologies + Sensors
  - a. Employees receive error messages on their Assistive Technologies in case of failure (Kolberg and Zühlke, 2015; Mrugalska and Wyrwicka, 2017; Slim et al., 2018)
  - b. Sensors contribute to the Poka-Yoke concept by avoiding incorrect components to be used thanks to part recognition (Kolberg and Zühlke, 2015; Mrugalska and Wyrwicka, 2017; Slim et al., 2018)
- 12. Kaizen & Decision support systems
  - a. Simulation can optimize the production system in terms of stocks, movements, overproduction and waiting (Baril et al., 2016; Stojanovic and Milenovic, 2019)

These represent the Smart Lean Operations that allow the development of a company from a “Management Controlled Factory” to a “Digitally (Supported) Controlled Factory”, and in the following we will see which are the Smart Lean Operations that allow the achievement of a LEAN4.0 dimension (i.e. the development into a “Socio Digital Controlled Factory”).

### ***Socio Digital Controlled Factory***

In the “Socio Digital Controlled Factory” managers aim to develop an agile factory by leveraging (i) fully connected information systems that provide real-time information and (ii) both local and cross-departmental improvement actions, with semi-autonomous teams that are fully responsible for parts of the value streams. In the “Socio Digital Controlled Factory” intelligent software is used to coordinate the teams and to link them to suppliers and (external) customers.

In this type of company, Lean practices and I4.0 technologies are widely combined, allowing to maximize the benefits of the two. As reported in the literature, in fact, Lean is a prerequisite to fully exploit the potentials of Industry 4.0 technologies, and I4.0 technologies allow to maximize the benefits of Lean practices (Buer et al., 2020, 2018; Kamble et al., 2019; Nascimento et al., 2019; Rossini et al., 2019; Sanders et al., 2017), and therefore their

integrations allow to maximize the benefits of the two (Tortorella and Fettermann (2017) stated that a concurrent implementation of lean manufacturing and Industry 4.0 leads to larger performance improvements than implementing only one of them). The combination of Lean practices and I4.0 technologies that we have found in WP4 and that enables a “Socio Digital Controlled Factory” are the following (for more detailed information on how to combine in practice a specific Lean practice with I4.0 technologies the reader should refer to the corresponding papers (reported below) discussing such combinations):

13. Continuous flow & Sensors + Big Data
  - a. The combination of Sensors and Big Data (and Data analytics) allows to achieve real-time exact tracking of inventory that enables the avoidance of flow disruption as a consequence of errors in inventory (Pereira et al., 2019; Valamede and Santos Akkari, 2020)
14. Continuous flow & Sensors + Big Data + Cloud computing
  - a. The combination of these three technologies allow to react promptly to incidences thanks to real-time KPIs calculation and monitoring (Rauch et al., 2016)
15. Continuous flow & Sensors + Big Data + Cloud computing + Decision support systems
  - a. Sensors and Big Data can provide real-time data that can be used as input in simulation tools (obtaining a simulation-based real-time solution) in order to improve the continuous flow by detecting bottlenecks and by reducing inventory levels (Dallasega et al., 2017; Lu and Yue, 2011; Rosin et al., 2020)
  - b. Simulation-based real-time solution allows to reduce the inventory levels and to assure production flow (Dallasega et al., 2017; Krenczyk et al., 2018; Snyman et al., 2017)
16. Continuous flow & Sensors + Big Data + Cloud computing + Advanced Algorithm
  - a. The integration of these technologies allows to optimize the scheduling of the material handling systems (G. Fragapane et al., 2020)
17. Continuous flow & Integrative technologies
  - a. Integrative technologies contribute to ensure a continuous flow by allowing systems to adjust autonomously production planning (Wagner et al., 2017)
  - b. By enabling an enhanced interconnection and communication between cells and workstations, Integrative technologies allow a flexible, fast and high-quality material flow (Schumacher and Sihm, 2016; Thoben et al., 2017)
18. Continuous flow & Integrative technologies + Advanced algorithm
  - a. The combination of these two technologies support continuous flow by enabling auto-adaptive production planning in the case of a capacity constraint in production (Shrouf et al., 2014; Tortorella et al., 2019; Wagner et al., 2017)
  - b. Their integration allows to create a proper flow within the supply chain, without any interruption, bottlenecks or delays (Bittencourt et al., 2019; Güner et al., 2012; J. Zelbst et al., 2014; Kolberg and Zühlke, 2015; Lee et al., 2015)
19. Pull & Sensors + Integrative technologies
  - a. Sensors recognize missing and empty bins automatically and Integrative technologies can trigger replenishment (Kolberg and Zühlke, 2015; Rosin et al., 2020; Sanders et al., 2016)
20. Pull & Sensors + Big Data + Cloud computing + Advanced Algorithms



- a. The combined use of these technologies allows to automatically adjust e-Kanban parameters to changes in batch sizes, market demands, work plans or cycle times (Ardalan and Diaz, 2012; Hermann et al., 2016; Kouri et al., 2008; Mayr et al., 2018)
- 21. SMED & Sensors + Big Data + Cloud computing + Advanced algorithms + Integrative technologies
  - a. The combination of these technologies can provide real-time data to enable substantial setup time reduction through self-optimisation of machines and workpiece-machine communication (Brettel et al., 2014; Kolberg et al., 2017; Satoglu et al., 2018)
- 22. TPM & Sensors
  - a. Sensors support TPM by sending error notifications when a machine breaks down (Davies et al., 2017; Sanders et al., 2016; Slim et al., 2018)
- 23. TPM & Sensors + Big Data + Cloud computing
  - a. These technologies allow to carry out predictive maintenance, where failures are predicted by detecting abnormal situations based on data from the past and/or other machines (Campos, 2009; Lee et al., 2014; Moeuf et al., 2018; Zhang et al., 2019)
- 24. TPM & Integrative technologies
  - a. In case of a breakdown, Integrative technologies allow to contact other machines for taking over the workload, hence mitigating the impact of the breakdown (Lucke et al., 2008)
- 25. TPM & Advanced algorithm
  - a. After predicting failures, Advanced algorithm can take actions that make the maintenance planning, forecasting, spare parts logistics easier and more efficient (Porter and Heppelmann, 2014; Sanders et al., 2017)
- 26. Jidoka & Sensors
  - a. Sensors allows an automatic trigger of fault-repair actions (Romero et al., 2019; Slim et al., 2018)
- 27. Jidoka & Decision Support Systems
  - a. Decision Support Systems (e.g. simulations) can mitigate the effects of failure in the productive process (e.g. by simulating different recovery strategies) (Adeyeri et al., 2015)
- 28. Six sigma & Advanced algorithm
  - a. Advanced algorithm allows continuous improvement activities thanks to conventional statistical methods applied to the data (Davies et al., 2017)
- 29. Six Sigma & Sensors + Big Data + Cloud computing
  - a. The combination of these technologies allows to automatically capture key production metrics (Davies et al., 2017; Ghobakhloo and Fathi, 2019; Nicoletti, 2013; Schuh et al., 2015; Stojanovic et al., 2015)
- 30. Six Sigma & Sensors + Big Data + Cloud computing + Advanced algorithms
  - a. Production problems can be anticipated through the collection of data, their analysis and the comparison with previous data (Davies et al., 2017)
- 31. Customer involvement & Sensors + Big Data

- a. The combination of the two enables to reduce communication times and costs and to increase efficiency and value added for customer providing real-time information directly in customer's information system (Astola et al., 2017)
  - b. It is possible to better identify customers' needs and behaviours thanks to the possibility to track usage data and analyse them (Shrouf et al., 2014)
- 32. Customer involvement & Sensors + Big Data + Cloud computing
  - a. These technologies enable customer-oriented real-time key performance indicators for quality, delivery time and costs (Wagner et al., 2018)
- 33. Customer involvement & Big Data
  - a. Big Data can enhance the forecast quality by facilitating extreme complex calculations and processing of relationship between needs and functions for large volume of data (Mayr et al., 2018; Pagliosa et al., 2019)
- 34. Customer involvement & Integrative technologies
  - a. Integrative technologies allow to postpone the start of the freeze period by keeping customers informed about the actual production connecting elements in the supply chain thanks to horizontal integrating digitized mechanisms (Cannata et al., 2008; Douaioui et al., 2018; Foidl and Felderer, 2016; Ivanov et al., 2016)
- 35. Supplier integration & Sensors
  - a. Sensors allow to enhance supplier credibility by tagging every item: it ensures to send the right products to the correct destinations, to reduce the lead times of distribution (by optimizing the travel routes) and a supplier is empowered to comment when exactly his goods would reach the customer (Bose and Pal, 2005; Caballero-Gil et al., 2013)
- 36. Supplier integration & Cloud computing
  - a. The use of Cloud computing and mobile computing services (smartphones and tablets connected to the internet and common cloud for example) allows effective supplier feedback thanks to an easy integration and relationship between business partners (Schmidt et al., 2015)
- 37. Supplier integration & Integrative technologies
  - a. Integrative technologies allow to synchronize data of products and production processes by sharing them beyond the boundaries of individual industries (Brettel et al., 2014)
- 38. Kaizen & Sensors + Big Data + Cloud computing
  - a. Sensors allow to have real-time data tracking (i.e. dynamic value stream mapping) that can be used to give instant visual feedback regarding performance (KPI) and provide transparency and better communication between production stakeholders (Moica et al., 2018; Wagner et al., 2017; Zhong et al., 2016a, 2016b)
  - b. Sensors can assist 5S by identifying and localizing objects, hence reducing the searching time (Mayr et al., 2018)
- 39. Kaizen & Assistive technologies
  - a. AR for example allow to visualize the dynamic value stream mapping (Davies et al., 2017; Tyagi and Vadrevu, 2015)
  - b. Assistive technologies assist 5S by guiding operators on where to place tools (hence replacing physical shadow boards) (Fescioglu-Unver et al., 2015)

40. People and teamwork & Sensors + Big Data + Cloud computing
  - a. These technologies allow a dynamic collaborative process facilitating information sharing and fostering cross-functional activities in organizations (Schuh et al., 2014)
41. People and teamwork & Assistive technologies
  - a. Assistive technologies facilitate workers collaborations and involvement in the company by providing interconnectivities among workers (Schuh et al., 2015)
  - b. Assistive technologies facilitate employees' training providing additional information to the employee on the tasks to be performed and providing real-time feedback on errors (Al-Ahmari et al., 2016; Longo et al., 2017; Segovia et al., 2015)

Now that we have seen which are the combinations of Lean practices and I4.0 technologies that enable the development of a company into a “Socio Digital Controlled Factory” (passing first through a “Digitally (Supported) Controlled Factory”), we have to understand how managers try to put in place these combinations: do they first introduce the Lean practices and then, once these are in place, they introduce the I4.0 technologies? Or do they first adopt the I4.0 technologies and only after that they implement Lean practices? Or do they try to introduce both Lean practices and I4.0 technologies simultaneously? We build on this in the next Section, for then better discussing this in D7.2.

## 2.4 Towards a LEAN4.0 company: insights about the path

As stated before, many researchers suggest that there is a relationship between Lean and I4.0 technologies (Buer et al., 2020, 2018; Kamble et al., 2019; Nascimento et al., 2019; Rossini et al., 2019; Sanders et al., 2017). A lot has been written about how Lean helps to develop technology: as researchers state, a certain level of Lean is necessary since leanness reduces the complexity of the processes on which I4.0 technologies might be helpful for. In this way of thinking, Lean helps to develop the technology maturity. On the other hand, there are researchers that state that I4.0 technologies also help to develop Lean in an organization: I4.0 technology helps to obtain data that can support process innovation or Lean improvement. It is hence clear that the interaction between Lean and I4.0 technologies is beneficial, and that they can benefit from each other. However, it is still unclear (i) which trajectory organizations follow to implement LEAN4.0 and (ii) what is the optimal way to implement LEAN4.0 in the organization. To answer these questions, we carried out an exploratory study (exploratory because the results are based on a small amount of interview), that allow us to gain some insights about this. More in details, we have considered three pilot projects carried out in our project (to not disclose any confidential information, the three companies will be simply refer to as Company A, Company B and Company C), investigating which trajectory they have been taking for their journey towards a LEAN4.0 dimension (i.e. towards a “Socio Digital Controlled Factory”), and we elaborate on this next. Specifically, the first step was that to map the initial status of the company with respect to the “Lean improvement maturity level” and to the “Technology maturity level” and see whether these companies are “*Management Controlled Factories*”, “*Digitally (Supported) Controlled Factories*”, “*Socio Digital Controlled Factories*”, or in transition towards one of the last two, for then following their evolution (i.e. trajectory) till their current situation.

### Case 1 – Company A

Concerning the starting point of Company A, the internal process was not fully under control and the maximum capacity of that way of working was reached. Specifically, the “Lean improvement maturity level” was such that the Lean practices adopted were applied only locally, not over the departments. There were also a lot of wastes, many movements, reworks, waiting times, and also a lack of standardization. Dealing with the “Technology maturity level”, some advanced technologies such as self-picking tower and semi-autonomous products pickers were used, but also at a local level. The starting point for the “Lean improvement maturity level” was hence between the first and second level (i.e. “Ad Hoc” and “Structured and Dedicated”, respectively), and similar for the “Technology maturity level” (green dot in Figure 4).

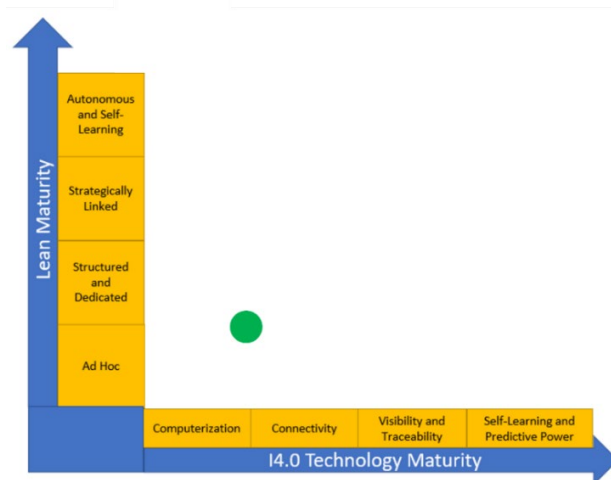


Figure 4. Starting point in terms of Lean and I4.0 maturity level for Company A

To develop Company A into the final goal of a LEAN4.0 company, managers decided to follow a Lean-driven journey. This means that Company A tried first to have the process under control and to develop the Lean thinking and the continuous improvement routines, and then to invest in the technologies. In fact, they invested a lot in Lean and continuous improvement, trying (i) to develop even more pull and flow within the company, (ii) to do cross-departmental value stream analysis, and (iii) to develop few kaizen teams working and doing their best to develop and get the process more under control. However, as suggested in the taxonomy in D1.2 where no company was found in the region of high Lean maturity level and low I4.0 maturity level (see Section 2.2), Company A reached a point where I4.0 technologies were needed to develop themselves even further, and they implemented some I4.0 technologies to allow connectivity and some others (such as simulation tools). At the end of this step, MCB positioned itself in the third “Lean improvement maturity level” and between the second and the third “Technology maturity level” (see Figure 5).

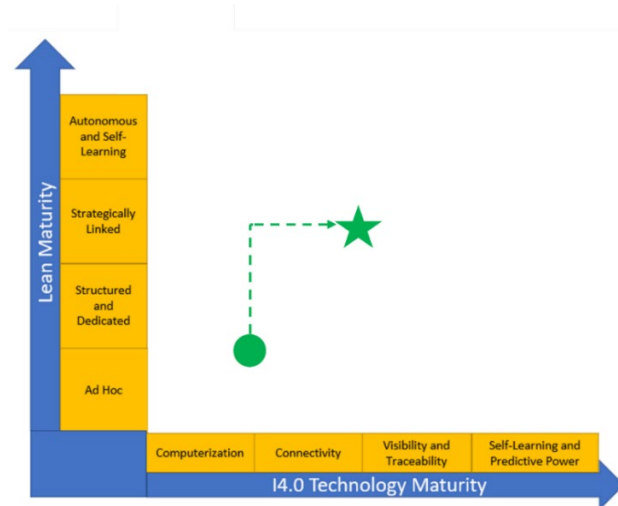


Figure 5. Starting (circle) and end (star) point in terms of Lean and I4.0 maturity level for Company A

Company A has now completely reached a “Digitally (Supported) Controlled Factory” dimension, which hence confirms to be a mandatory preliminary step in the achievement of the “Socio Digital Controlled Factory” dimension. Company A is now busy developing further, to achieve this “Socio Digital Controlled Factory” dimension, and this is discussed in the Section related to D7.2. Company A managers were satisfied by a Lean-driven journey since, using a statement from the director of operation management, “developing in Lean first helps to clarify what technologies can be helpful for future processes”.

### Case 2 – Company B

Dealing with Company B, the starting point for the “Lean improvement maturity level” was between level 1 and 2: there were some Lean initiatives on the shop floor, but these were mainly locally (for example they made use of 5S and improvement boards), there was no standardization (employees found hard to work on a structured way). The starting point for the “Technology maturity level”, instead, was between level 2 and 3: they had some successful advanced technology implementation (such as a cardex system and an advanced laser cutting machine). The starting point is summarized in Figure 6 by the blue dot, and based on the taxonomy, Company B almost falls within the “Digitally (Supported) Controlled Factory” dimension (they need to reach level 2 of the “Lean improvement maturity level” to reach such dimension).

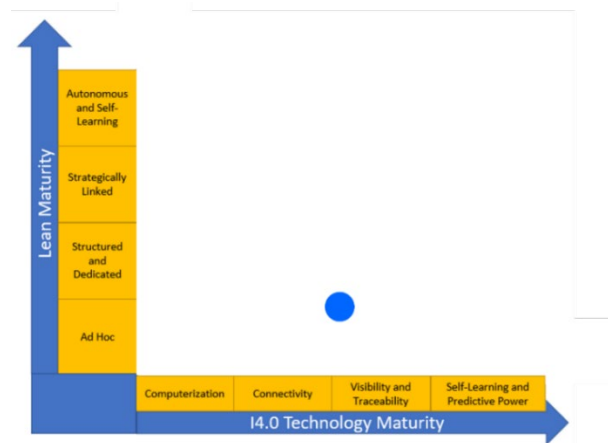


Figure 6. Starting point in terms of Lean and I4.0 maturity level for Company B

To develop Company B into the final goal of a LEAN4.0 company, managers decided to follow a diagonal trajectory, improving both in “Lean improvement maturity level” and in “Technology maturity level” at the same time, leading to the final point where an ERP system was implemented and investments in continuous improvement and leanness were made, leading to a structured and standardized way of working (the final point is depicted as a blue star in Figure 7).

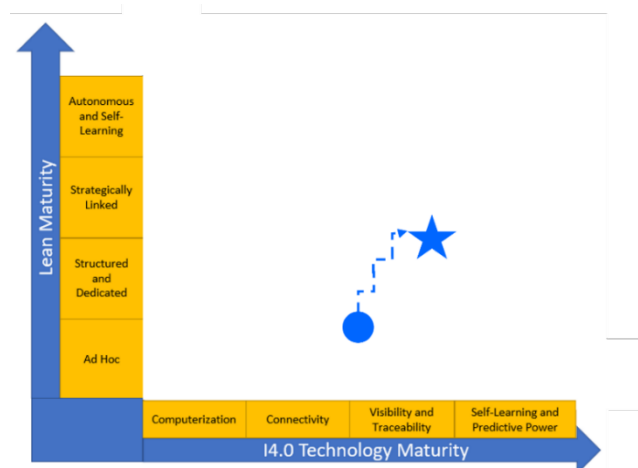


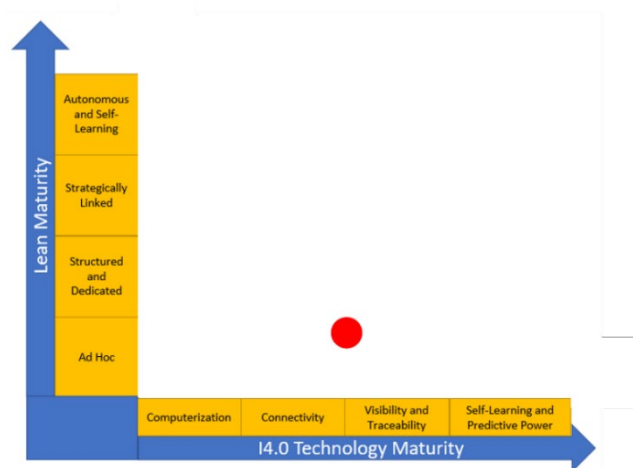
Figure 7. Starting (circle) and end (star) point in terms of Lean and I4.0 maturity level for Company B

Company B has now reached a fully “Digitally (Supported) Controlled Factory” dimension, and is moving towards the final goal of the “Socio Digital Controlled Factory” dimension. From what emerged from this pilot project, although following a diagonal trajectory is the shortest way towards the “Socio Digital Controlled Factory” dimension, following such trajectory is difficult. In fact, it is not easy to combine Lean development projects together with I4.0 projects. On the one hand, when you want to become more Lean mature, this is time consuming because employees have to develop a new routine and a new way of thinking, so it takes time before they think in Lean terms. On the other hand, I4.0 technologies are costly, and often managers want to implement these technologies as soon as possible and they want to make sure that they operate as soon as possible. So, when you want to combine these slow Lean trajectories and these fast I4.0 trajectories there are some frictions. Also managers, when interviewed, suggested that a Lean-driven approach would have been less complicated: the

manager of the Operations Office stated that “If we did some Lean development before investing in I4.0, the project would have been faster and less costly than what we did”.

### ***Case 3 – Company C***

The starting point for Company C with respect to the “Lean improvement maturity level” was between level 1 and 2: there are some learnings and improvements procedures, but these are neither structured (for example with the use of A3 or structured problem solving methodologies) nor shared across other teams: problem solving were ad-hoc and done in small groups, and the learning and interventions are not stored or shared across other teams. The starting point for the “Technology maturity level”, instead, was quite high, between level 2 and 3: Company C has invested a lot in technology in the past, for example investing in robotic production systems. The starting point is summarized in Figure 8 by the red dot, and based on the taxonomy, Company C almost falls within the “Digitally (Supported) Controlled Factory” dimension (as for Company B, they need to reach level 2 of the “Lean improvement maturity level” to reach such dimension).



*Figure 8. Starting point in terms of Lean and I4.0 maturity level for Company C*

To develop themselves into the final goal of a LEAN4.0 company, Company C decided to follow a technology-driven journey, and therefore, to cope with the increased in diversity and number of products, they invested in I4.0 technologies, such as flexible advanced robotic solutions, AR and VR, as well as in the infrastructure to support it. However, at some point they experienced that although new and technologically advanced solutions were bought, they were not able to achieve the capacity needed to cope with the increased demand for more and diverse products. So, Company C had to invest and structurally improve all the processes in order to get optimal effects from the implemented technological solutions, and they focused on improving the Lean level by using A3 and structured problem solving methodologies and by cross-departmental collaborations (the final point is shown as a red star in Figure 9).

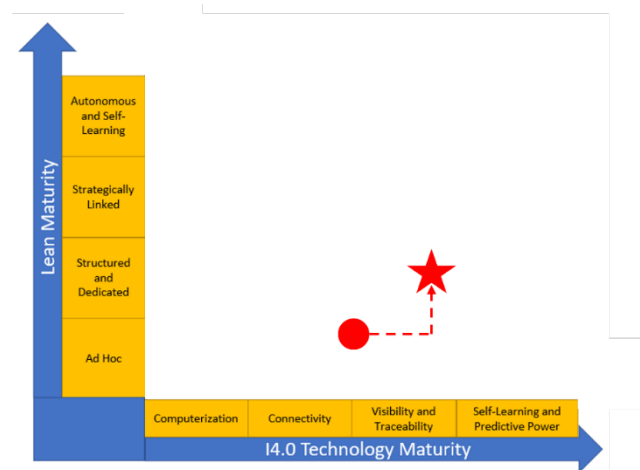


Figure 9. Starting (circle) and end (star) point in terms of Lean and I4.0 maturity level for Company C

Company C has now reached a fully “Digitally (Supported) Controlled Factory” dimension, and is moving towards the final goal of the “Socio Digital Controlled Factory” dimension. From what emerged from this pilot project, adopting a technology-driven journey was not the optimal solution for Company C, especially considering the low starting level of Lean maturity. Company C recognized that, when introducing complex technologies, there is the need to invest in people first, who has to improve certain skills and to change work routines and mentality: people do not only need the time to learn how to use the new technologies, but they also need time to be fully onboard with the changes, and to achieve so it is important that it is explained to them why these changes are important and required and what it is expected from them. Moreover, Company C realized that the implementation of I4.0 technologies is a wide process that goes all over the organization, so it’s important that managers and team leaders have an holistic view of the overall process.

### **General considerations**

Based on the three cases that we have just described, we can see that there are three paths (previously referred to as journeys) that a company can take towards a “*Socio Digital Controlled Factory*” dimension, i.e. (i) Lean-driven path, (ii) technology-driven path and a (iii) diagonal path, and this is similar to what reported by Sengupta et al. (2021). According to what seen from our three case studies, it emerged that the Lean-drive path was probably the most suitable path, but we cannot draw any general conclusions due to limited number of companies considered for the analysis. To try to gain some more insights, we carried out a survey among companies belonging to the HAN Lean-QRM Center, collecting feedback on which paths they think it is the most suitable to reach the “*Socio Digital Controlled Factory*” dimension, and the results are reported in Figure 10.



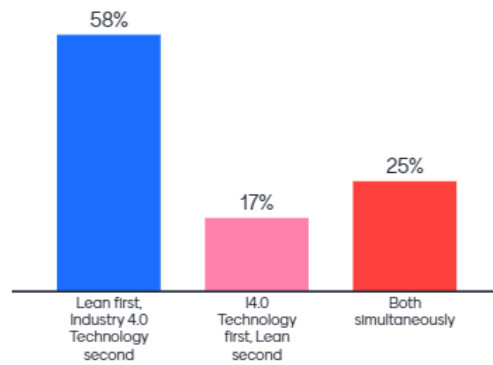


Figure 10. Results of the survey about the preferred path towards the “Socio Digital Controlled Factory” dimension

We can see that most of the companies think that the best way to move towards a “*Socio Digital Controlled Factory*” dimension is a Lean-driven path, where Lean is applied first, and I4.0 technologies second. The other two paths are also considered possible, and therefore cannot be excluded.

In the next Section we will see the different phases and decision gates that constitute the development of a company towards the “*Socio Digital Controlled Factory*” dimension, and we will consider all these three different paths. Moreover, based on the experience gained from the pilot projects, we will also see how the Blended Network Action Learning methodology can support each of the different paths.

### 3 D7.2 - Implementation process for Smart Lean Operations

#### 3.1 Introduction

The aim of the previous Section (that corresponds to Deliverable D7.1) was that to develop and formalize a reference model for Smart Lean Operations. In this section (that corresponds to Deliverable D7.2), a standard implementation process to support such reference model will be provided. Specifically, while D7.1 provides managers information about the initial situation of their company and about which combination of Lean practices and I4.0 technologies can be beneficial in achieving their goal of becoming a LEAN4.0 company, D7.2 supports them in determining which of the three paths identified in the previous Section (i.e. (i) Lean-driven path, (ii) technology-driven path and (iii) diagonal path) is the most suitable to achieve their goal. It is worth mentioning that there is not an absolute best path, but what is the most suitable path for one company, might not be the most suitable for another company, even if the starting point might be the same. The suitability of a path, in fact, depends also on strategic decisions which might be outside of the control of the Operations Managers (for example, if the head quarter decides to prioritize the adoption of technologies over the adoption of Lean, then the choice of a technology-driven path is the only one possible), and/or on context factors such as substantial changes in the demand of products which requires new investments in technology and/or the inability to borrow money from the bank. As we will see in the following, it is important to recognize key Lean and Industry 4.0 (and LEAN 4.0) decision variables and to organize them in one or more consistent scenarios. These scenarios can be seen as roadmaps. These scenarios are an important support for Operations managers when applying the ‘learning by doing and reflecting’ BNAL methodology (see WP3.0 and WP6.1). The alpha, beta and gamma learnings, gained from using BNAL, help Operations managers to select a scenario to

follow and to make appropriate LEAN4.0 decisions. The operations managers can also learn from the BNAL learnings of other managers, as depicted in BNAL A3's which resulted in the LEAN4.0 project (see WP6). For the development of scenario's, we applied the embedded case study methodology of Formative Scenario Analysis, whose details can be found in the Appendix). In the following we will describe in detail the implementation process.

### 3.2 Implementation process

In the following we consider the example of a company whose starting point corresponds to the “*Management Controlled Factory*” dimension (however, the implementation process that we will describe in the following holds for any starting point). So, referring to the taxonomy of smart Lean operations developed in WP1 (see Figure 1), the starting point is on the bottom left. This corresponds to a decision gate, indicated with a red dot in Figure 11.

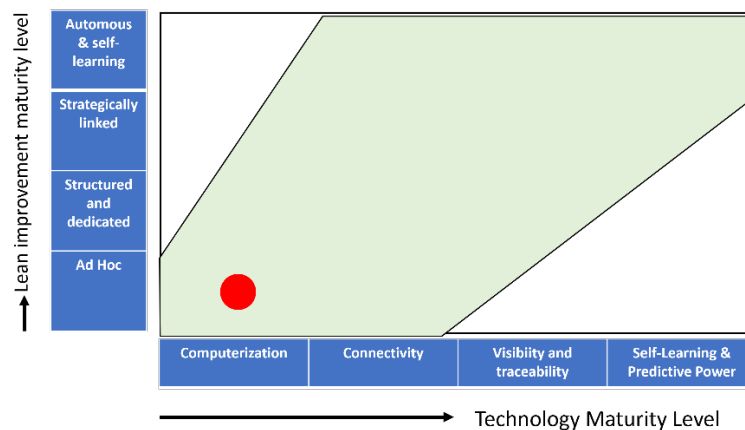


Figure 11. Decision gate (red dot) of the implementation process for Smart Lean Operations

From this point, in fact, managers have to decide what is their final goal and how to reach it. The final goal could be the “*Socio-Digital Controlled Factory*”, but it could also be the intermediate dimension of “*Digitally (Supported) Controlled Factory*”, or any other “location” in the green area of the taxonomy. To do so, managers can leverage the Formative Scenario Analysis (FSA, described in the Appendix). The FSA, in fact, is a useful supporting tool for managers to develop an effective **roadmap** towards the achievement of their final goal: FSA helps to clearly define the current situation, the possible scenario(s) that correspond(s) to the final goal, and to determine feasible (consistent) trajectories (i.e. paths) to arrive at the desired situations. Specifically, it helps identifying the pros and cons of each path and the correlated risks, so managers can choose wisely between the different possible options. The possible paths are many, but they can be classified in the three main categories identified before, i.e. (i) Lean-driven path, a (ii) technology-driven path, or a (iii) diagonal path, and they can lead to different final goals. Figure 12 reports an example of the three possible paths in the case of the final goal being the “*Digitally (Supported) Controlled Factory*” dimension.

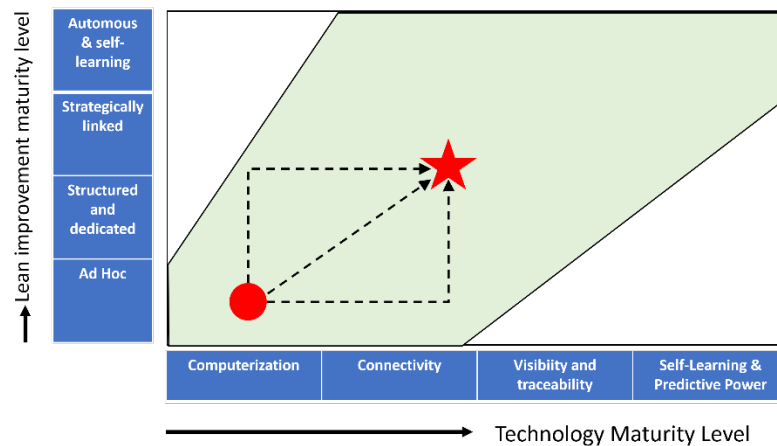


Figure 12. Possible paths in the case of the final goal being the “Digitally (Supported) Controlled Factory” dimension

However, the decision about the final goal and the chosen path are not definitive. In fact, managers have to periodically check the status of their development, to control, among others, (i) whether the current status matches the expected status, (ii) whether the final goal is still reachable or not, (iii) whether the identified scenario is still the most appropriate to reach the final goal or not, and (iv) whether the chosen path is still the most suitable or not. Let’s consider the following example to clarify. Managers of Company X have chosen to support all the workstations with expensive technologies to reach a certain final goal. However, after some months, the company goes through an economic crisis, and it is not possible to buy and implement all the technologies. By carrying out a periodic check, managers can promptly carry out alternative plans to solve this issue. An effective tool for carrying out such periodic check is the Lean tool of Plan-Do-Check-Act (PDCA). Specifically, it is important to carry out the PDCA not only to consider unpredictable events or results, but also to take into account the lessons learned in that period of time. In fact, as time passes in the development process, managers might learn and gain new knowledges that render certain scenarios unfeasible and might require to change path or scenario eventually. The BNAL methodology is a means to gather the learning in the chosen period of time or at the time that something happens which urges revision of the initially chosen scenario (roadmap). These learnings support the choice or adaptation of a scenario. Also BNAL learnings provided by LEAN4.0 partners and future documented BNAL learnings may provide useful information for scenario selection. Specifically, from the pilot projects we have learnt that:

- A Lean-driven path
  - Asks for continuous attention to keep enthusiasm and to learn (A3 method);
  - Management support is essential;
  - Requires to keep people aligned and to select people for projects before developing procedures;
  - Makes improvement plans visual (model, animation);
  - Takes time, not always visible what the learnings are.
- A technology-driven path
  - Is characterized by integration problems (integration in the whole VSM and in the information system);
  - Has the need for substantial resources from different functions in the organization;

- Is dependent on experts, mostly outside the company;
- Relies on suppliers: they need to be able to give sufficient support and there is the need to have clear agreements beforehand;
- Requires adaptability and flexibility;
- Is characterized by the risk of ordering too fast new technology without sufficient preparations.
- A diagonal path:
  - Has the risk of too many simultaneous projects;
  - Requires a balance between Continuous Improvement (lean learning focus) and digitalization, and this is not easy because of the difference in focus and tangibility.

And in general, we have learnt that

- Cooperation with University is experienced very positive – creates a knowledge network;
- ICT tools offer good networking opportunities. eXtended Virtual reality will increase possibilities for blended networking.
- There can be no blended network learning without blended network action! There is the requirement that at least some actors in the network can gain physical access to Gemba in order to carry out action and generate actionable knowledge.

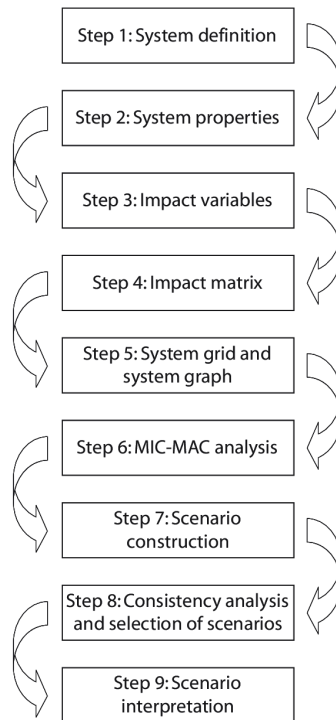
It is worth mentioning that the implementation process for the reference model for Smart Lean Operations herein described can be facilitated and improved by the results of WP1, WP3 and WP4. The Assessment tool for Smart Lean Operation developed in WP1 (i.e. D1.1.) can facilitate the FSA helping determining the current status and the final goal, while the Process Innovations within Smart Lean Operations identified in WP4 (specifically in D4.3.) can support the FSA helping to identify the possible scenario(s) that correspond(s) to the final goal. Furthermore, the BNAL methodology developed in WP3, and particularly its System Gamma, is extremely important in the periodic check of the status of the development process through the PDCA. System gamma, in fact, concerns the learnings from the project, and it is crucial that these learnings are understood and transferred to update the action plan (as mentioned before, the learnings might render certain scenarios unfeasible and might require to change path or scenario).

## Appendix

The Formative Scenario Analysis (FSA) is a scientific technique to construct well-defined sets of assumptions to gain insight into a case and its potential development. FSA provides a script describing steps that managers (or managerial teams) must take in response to the current state and possible future states of the company. A scenario, in fact, describes a hypothetical future state of a system and provides information on its development up to this state. This is done by introducing so-called impact factors. An impact factor is simply a system variable that describes the current state and dynamics of the case. Impact factors are also called impact variables. The art of scenario analysis consists of creating a sufficient set of impact variables and linking the variables in such a way as to gain a valid case description. In this way, scenario analysis provides consistent hypothetical future states of a case. The starting point for a scenario analysis is the case in its existing state. The state of the case varies depending on

the changes in and development of its internal and external system variables. The FSA procedure guides managers (or managerial teams) toward a differentiated and structured understanding of a case's current state and its dynamics.

FSA is a nine-step procedure that should be worked through sequentially (Figure A.1).



*Figure A1. The nine steps of the Formative Scenario Analysis*

### **Step 1: System definition**

First, managers (or managerial teams) must find a clear answer to the question "What is the case?" Sometimes, this question is not simple to answer. Many cases have fuzzy margins. Second, a specific perspective on the outcome of the case analysis must be determined. The critical question for this step is "Why is the scenario analysis being performed?".

### **Step 2: System properties**

The scenario analyst must mentally delve into the case in order to determine the factors that establish the current state of the case and its dynamics (i.e. impact variables). There are two proven strategies for determining these crucial impact variables.

One strategy is to perform a plus-minus analysis. Sometimes, it makes sense to perform separate plus-minus analyses, because what may be considered strengths from an economic perspective might be considered weaknesses from a social or environmental perspective. Thus, two or more plus-minus analyses should be performed. The more extended version of plus-minus analysis is the Strengths-Weaknesses-Options-Threats (SWOT) analysis, which also can be conducted at this step of FSA.

Another strategy for grasping the case structure and its dynamics is to study formerly planned projects or interventions. Usually, several plans for improving the case already have been proposed. Each plan generally provides insight into the structure and dynamics of the case, highlighting the case's potential while revealing sensitive features and factors that could have an impact on case development.

### **Step 3: Impact variables**

In general, the aim of this step is to develop a set of impact variables sufficient for valid description and modeling of the current state of the case and its dynamics. The selection and definition of impact variables or impact factors is the most crucial and time-consuming step of a scenario analysis. There are top-down and bottom-up procedures for clustering, ordering, and eliminating impact variables. Which procedure is recommended depends on the knowledge of the managers (or managerial teams). Usually, anyway, it is best if managers (or managerial teams) end up with no more than 20 variables. From these, according to the satisficing principle, not more than a dozen impact variables should be created.

### **Step 4: Impact matrix**

The formation of an impact matrix initiates the actual synthesis process. A cell of the matrix assigns (the absolute value of) the direct impact strength of one variable on another variable. In constructing the impact matrix, the managers (or managerial teams) have to determine the scale for the impacts. Because there is no natural scale for judging impact strength, the rating has to be assessed on a subjective scale. To formulate a scale for impact strength, the scenario analyst must link his or her case-specific knowledge with the available textbook or scientific knowledge about the variables under consideration. The scaling may have different degrees of refinement. Theoretically, any kind of scale between a simple, nominal 0,1 coding and an absolute scale using arbitrary rational numbers is possible. When rating the impacts between variables, the scenario analyst must be aware of several prerequisites and acknowledge potential biases. The following list outlines the six most important ones.

1. The analyst needs to assess the direct impact of one variable on another, which is not a simple task. It is particularly important that the analyst exclude any indirect impacts that a variable has via any other variable that has been defined. This requires that in the course of rating the mutual impacts, the analysts always remain aware of any other variables that are involved. For instance, if, in a subsequent step, the number of impact variables would be reduced and a variable cancelled, the ratings of some impacts could change, and, in principle, all ratings should be repeated.
2. The analyst has to construct causalities instead of correlations.
3. The analyst needs to rate the current impacts, not those that were present previously.
4. The analyst should provide a judgment that includes as much information as possible.
5. The analyst should make sure that the impacts are rated with respect to the specific case being considered, rather than rating general relations. This task is often made easier by encountering the case visually.
6. The analyst needs to be aware of judgment shifts in the course of filling out the impact matrix, e.g. burnout phenomenon and group choice shift.

Thanks to the Impact Matrix, it is possible to calculate “Activity” and “Passivity” (Figure A2).

$d_i \downarrow / d_j \rightarrow$	1	..	N	$a_{i,r}$	$a_{i,j} / a_{j,i}$
1	$a_{1,1}$	..	$a_{1,N}$	Activity $\sum_{j=1}^N a_{1,j}$ .. $\sum_{j=1}^N a_{N,j}$	Impact strength $a_{1,r} / a_{r,1}$ .. $a_{N,r} / a_{r,N}$
..	..	..	..		
N	$a_{N,1}$	..	$a_{N,N}$		
$a_{i,j}$	$\sum_{i=1}^N a_{i,1}$	..	$\sum_{i=1}^N a_{i,N}$	$a_{i,r} = \sum_{i=1}^N \sum_{j=1}^N a_{i,j}$	
$a_{i,j} * a_{i,r}$	Passivity $a_{1,1} * a_{1,r}$ .. $a_{N,N} * a_{N,r}$			Involvement	

Figure A2. General example of Impact Matrix

### Step 5: System grid and system graph

Step 5 simply provides a transformation of the information from an algebraic impact matrix to a geometrical system grid and system graph (Figure A3). Activity and sensitivity ratings are displayed in a system grid. A system grid is a conjoint display of the column and row sums. The plane is divided by a vertical and a horizontal line through the mean activity and sensitivity/passivity scores. Hence, the impact variables are partitioned into four sets.

The system graph is a structured network that presents a structural view of the system model. It visualizes how the different variables are interlinked.

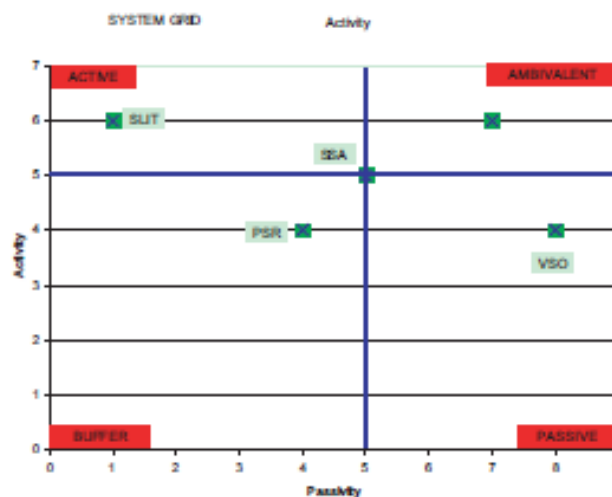


Figure A3. General example of the system graph

### Step 6: MIC-MAC analysis

Until now, we have considered only the direct impacts between system variables. Furthermore, our considerations were static. The goal of the MIC-MAC is to take the indirect impacts into account in order to gain a more detailed insight into the impact variables' importance from a System Dynamics perspective. The starting point of analysis is the impact matrix. For the MIC-MAC Analysis, this matrix needs to be coarsened, such that it contains information only on

whether there is a (strong) direct impact or no impact. To take into account the indirect impacts, the impact matrix is multiplied with itself repeatedly, and after each multiplication, the column sums and row sums are calculated. If this has been done often enough, the rankings of the column and row sums mostly become stable. The row sum is generally considered to be indicative of a variable's activity, including indirect impacts. Similarly, the column sum is indicative of a variable's passivity, including indirect impacts. The scores of direct and indirect impact activity (or passivity) have to be compared. The greater the difference between an impact variable's direct and indirect activity ratings, the more attention should be paid to it in scenario construction (see Step 6). If a variable's scores for its indirect impacts are higher than those for its direct ones, one might conclude that this variable is of higher importance than the managers (or managerial teams) had supposed.

### **Step 7: Scenario construction**

A scenario is simply a complete combination of levels of impact factors for all factors. At this point in the analysis, it becomes apparent that scenario analysts should be parsimonious in defining impact factors and their levels from the very beginning. Even so, for Step 7, the number of variables should be reduced out of the differentiated insight gained from the MIC-MAC Analysis. This can best be done by referring to the system grid and system graph. In conclusion, the insights provided by the MIC-MAC analysis and the system graph may help in selecting the variables most important to the system dynamics of the case.

### **Step 8: Consistency analysis and selection of scenarios**

Scenario selection is a two-step procedure for assessing possibility. First, we produce consistency measures for each scenario (consistency analysis is an analytic procedure for cleaning up a set of scenarios). These allow us to distinguish between consistent and inconsistent scenarios. The remaining set of consistent scenarios is what fills the funnel of the scenario trumpet. Second, we have to screen this set in order to select a small number of scenarios that represent the set of future states of our case.

### **Step 9: Scenario interpretation**

We will describe briefly four ways of interpreting scenarios.

*Conversation.* The most natural way of interpreting scenarios is by simply discussing them—their differences, their genesis, and their quality with respect to certain criteria and perspectives.

*Evaluation.* Evaluation can be thought of as a specific form of interpretation. Usually, evaluations are inherent parts of most case discussions, but there are both soft and hard methods of evaluation. We call an evaluation soft if the criteria and procedure for evaluation are not explicitly revealed, but rather are implicitly involved in the inferences and conclusions. In contrast, we consider an evaluation procedure hard if the criteria and procedure are made explicit. This means that they are displayed in a way that allows at least enough objectivity for there to be a high probability that another evaluator who starts with the same premises would end up with the same conclusion.

*Best Reply Strategies.* Another way of working with scenarios is to think about which intervention or strategy would be the best for the case in response to a certain scenario.



There are many ways to determine, and many criteria for defining, which of a set of strategies is the best. A well-known robust strategy is the max-min strategy. This strategy presumes that, for all the possible intervention options (i.e., variants), the worst global scenario will occur. Under this (pessimistic) assumption, the maximizing variant is chosen.

*Scenario Manipulation.* One way of understanding a scenario is through studying and interpreting it by manipulating the impact strengths. This manipulation provides information about the sensitivity of the case structure and, therefore, where the case can be affected.

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