IPS Instituto Politécnico de Setúbal
Escola Superior de Tecnologia de Setúbal

DÁRIO MIGUEL DA SILVA PELIXO

CPPS-3D: A METHODOLOGY TO SUPPORT CYBER PHYSICAL PRODUCTION SYSTEMS DESIGN, DEVELOPMENT AND DEPLOYMENT

Master's dissertation in Production Engineering

SUPERVISOR

Prof. Doctor Pedro Filipe do Carmo Cunha, ESTSetúbal/IPS

December 2019

DÁRIO MIGUEL
DA SILVA PELIXO

CPPS-3D: A METHODOLOGY TO SUPPORT CYBER PHYSICAL PRODUCTION SYSTEMS DESIGN, DEVELOPMENT AND DEPLOYMENT

JURY

President: Prof. Doctor José Filipe Castanheira Pereira Antunes Simões, ESTSetúbal/IPS

Vowel: Prof. MSc Fernando Henrique Mayordomo Cunha, ESTSetúbal/IPS

Supervisor: Prof. Doctor Pedro Filipe do Carmo Cunha, ESTSetúbal/IPS

December 2019

To Rita for the amazing adventure here.

Acknowledgements

In a very special way, I am deeply thankful to my supervisor Prof. Pedro Cunha for all his availability, support, commitment, incentive, critical spirit and knowledge transmitted throughout our time working together which allowed for the becoming of this moment.

A special thank you is also due to Prof. Rui Madeira for the sharing of knowledge about his experience in the developments carried out within the PRODUTECH project which turn out to be of fundamental importance for this endeavour.

I want to thank Prof. José Simões, Prof. Maria João Carmezim and Prof. Ricardo Cláudio for all their support and guidance throughout all *Final Project* curricular units which have greatly contributed to this work.

A thank you also to Sara Miriam Silva, Amina Mateus, Anabela Ramos and others of the ESCE/IPS library staff for their sympathy, availability and valuable bibliography related help.

To my parents and brother for the affection and unconditional support shown along this long journey.

Finally to Rita Quendera Silva for everything we've been through together, for the eternal good mood and the never-ending support and affection in both failure and success.

To all I'm genuinely grateful.

Abstract

Cyber-Physical Production Systems are widely recognized as the key to unlock the full potential benefits of the Industry 4.0 paradigm. Cyber-Physical Production Systems Design, Development and Deployment methodology is a systematic approach in assessing necessities, identifying gaps and then designing, developing and deploying solutions to fill such gaps. It aims to support and drive enterprise's evolution to the new working environment promoted by the availability of Industry 4.0 paradigms and technologies while challenged by the need to increment a continuous improvement culture. The proposed methodology considers the different dimensions within enterprises related with their levels of organization, competencies and technology. It is a two-phased sequentially-stepped process to enable discussion, reflection/reasoning, decision-making and action-taking towards evolution. The first phase assesses an enterprise across its Organizational, Technological and Human dimensions. The second phase establishes sequential tasks to successfully deploy solutions. Is was applied to a production section at a Portuguese enterprise with the development of a new visual management system to enable shop floor management. This development is presented as an example of Industry 4.0 technology and it promotes a faster decision-making, better production management, improved data availability as well as fosters more dynamic workplaces with enhanced reactivity to problems.

Keywords: Production systems, Industry 4.0, Cyber-Physical system, Problem-solving, Product development, Continuous improvement

Table of contents

Acknowledgements iv

Abstract v

Table of contents vi

List of figures x

List of tables xii

List of abbreviations and acronyms xiii

Chapter 1. Introduction 1

1.1. Scope 2

1.2. Context and outcomes 2

1.3. Structure 4

Chapter 2. Industry 4.0 background knowledge 6

2.1. Concept and development 7

2.2. Technological dimension 15

2.2.1. Cyber-Physical Production System 20

2.3. Human dimension 26

2.4. Organizational dimension 29

2.5. Background knowledge supporting methodology design and proposal 33

2.5.1. Lean management 33

2.5.2. Six Sigma and DMAIC methodology 42

2.5.3. Quality Function Deployment 43

2.5.4. Failure Mode and Effect Analysis 44

2.5.5. Seven basic tools of quality 45

2.5.6. Axiomatic Design *46*

2.5.6.1. Customer needs and the Kano model 47

2.5.7. Theory of Inventive Problem-solving *48*

2.5.8. Migration strategies *49*

2.5.9. Plan-Do-Check-Act cycle *50*

2.5.10. German VDI/VDE Guideline 3695 .... *52*

Chapter 3. CPPS-3D: A methodology to support cyber physical production systems design, development and deployment 54

3.1. CPPS-3D Overview 55

3.2. CPPS-3D Assessment phase 60

3.2.1. Status step *60*

3.2.1.1. FP1. Organizational dimension 61

3.2.1.2. FP2. Technological dimension 62

3.2.1.3. FP3. Human dimension 63

3.2.2. Analysis step *63*

3.2.2.1. FP4. Evaluation 64

3.2.2.2. FP5. Gap identification 65

3.2.3. Vision step *65*

3.2.3.1. FP6. Action definition 66

3.2.3.2. FP7. Planning 66

3.2.4. CPPS-3D Assessment table guide and radar *67*

3.3. CPPS-3D Project development phase 69

3.3.1. Design step *69*

3.3.1.1. FP8. Project aim 70

3.3.1.2. FP9. Concept planning 71

3.3.1.3. FP10. Detail planning 72

3.3.2. Deployment step *73*
3.3.2.1. FP11. Preparation for realization 73
3.3.2.2. FP12. Ramp up management 74
Chapter 4. Case study synthesis and discussion 76
4.1. Case study synthesis 77
4.1.1. Case study Assessment *78*
4.1.1.1. FP1. Organizational dimension 78
4.1.1.2. FP2. Technological dimension 79
4.1.1.3. FP3. Human dimension 79
4.1.1.4. FP4. Evaluation 80
4.1.1.5. FP5. Gap identification 80
4.1.1.6. FP6. Action definition 80
4.1.1.7. FP7. Planning 81
4.1.1.8. Assessment guide table and radar 81
4.1.2. Case study Project Development *83*
4.1.2.1. FP8. Project aim 84
4.1.2.2. FP9. Concept planning 86
4.1.2.3. FP10. Detail planning 89
4.2. Case study results and discussion 89
Chapter 5. Conclusions and future work 91
5.1. Conclusions 92
5.2. Future work 94
Bibliography 95
Appendix I. Assessment guide table and ratings A.1
Appendix I.1. CPPS-3D Assessment guide table Template and Radar A.2
Appendix I.2. CPPS-3D Organizational dimension level concepts A.3

Appendix I.3. CPPS-3D Sustainability level concepts................................ A.3
Appendix I.4. CPPS-3D Technological dimension level concepts A.4
Appendix I.5. CPPS-3D Continuous improvement level concepts A.5
Appendix I.6. CPPS-3D Human dimension level concepts A.5
Appendix I.7. CPPS-3D Communication level concepts A.6

List of figures

Figure 2.1 - The four stages of Industrial Revolutions 7

Figure 2.2 - Reference Architectural Model for I4.0 8

Figure 2.3 - Industry 4.0 concept 9

Figure 2.4 - Clusters of I4.0 status measuring in production across EU 11

Figure 2.5 – Profile statistics of Portuguese enterprises and top managers 12

Figure 2.6 - Classification of production systems 16

Figure 2.7 - Estimation of current research gaps towards I4.0 17

Figure 2.8 - Convergence of virtual world and physical world technologies 18

Figure 2.9 - Group technologies and tools for industry 4.0 19

Figure 2.10 - Scenario of a cyber-physical production system 21

Figure 2.11 - CPPS layers 21

Figure 2.12 - Transition process from Mechatronics to IoT 23

Figure 2.13 - Relationships of increasing abstraction 23

Figure 2.14 – Evolution of automation hierarchy to CPS-based automation 24

Figure 2.15 - 5C architecture for implementation of CPPS 25

Figure 2.16 - Matrix for optimal collaboration of Human and CPPS 27

Figure 2.17 – Complementary 5C architecture for Cyber Human Systems 28

Figure 2.18 - Framework for management challenges on I4.0 30

Figure 2.19 - Forms of waste of Time 35

Figure 2.20 - Commonalities of LM and I4.0 37

Figure 2.21 - Synergy between I4.0 and Lean 38

Figure 2.22 - Simplified VSM with process and value stream KPI 39

Figure 2.23 - Basic configuration of a House of Quality 43
Figure 2.24 - Blank FMEA worksheet... 44
Figure 2.25 - Seven basic quality tools 45
Figure 2.26 - Axiomatic Design methodology.. 47
Figure 2.27 - Kano model... 47
Figure 2.28 - Inventive problem-solving algorithm... 48
Figure 2.29 - Migration strategies comparison (left) and recursivity (right)....... 49
Figure 2.30 - PDCA cycle... 51
Figure 2.31 - VDI/VDE Directive 3695... 52
Figure 3.1 - CPPS-3D dimensions and relationships 56
Figure 3.2 - CPPS-3D methodology.. 58
Figure 3.3 - CPPS-3D vertical detail concepts 59
Figure 3.4 - CPPS-3D assessment steps.. 60
Figure 3.5 - CPPS-3D Project development steps 69
Figure 4.1 - Robotic-welding section... 77
Figure 4.2 - CPPS-3D overview 77
Figure 4.3 - CPPS-3D Assessment workflow... 78
Figure 4.4 - CPPS-3D enterprise assessment radar.. 82
Figure 4.5 - CPPS-3D Project Development workflow 83
Figure 4.6 - Proposed system configuration.. 86

List of tables

Table 2.1- Global competitiveness rankings for I4.0 10

Table 2.2 - Summary of I4.0 Maturity Models 13

Table 2.3 - DMAIC phases and tools 42

Table 2.4 – Phase comparison of PDCA, DMAIC, A3 and 8D 51

Table 3.1 - CPPS-3D Status Step 60

Table 3.2 - CPPS-3D Analysis Step 64

Table 3.3 - CPPS-3D Vision Step 66

Table 3.4 - CPPS-3D Design Step 70

Table 3.5 - CPPS-3D Deployment Step 73

Table 4.1 - Enterprise assessment table 82

Table 4.2 - FR-DP mapping 87

Table 4.3 - DP-PV mapping 88

List of abbreviations and acronyms

AAS	Automated Assembly System
AD	Axiomatic Design
API	Application Programming Interface
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AM	Additive manufacturing
AR	Augmented Reality
BLE	Bluetooth Low Energy
CAD	Computer Aided Design
CE	Concurrent Engineering
CHS	Cyber-Human System
CIM	Computer Integrated Manufacturing
CIPS	Computer Integrated Production System
CMM	Coordinate Measuring Machine
CN	Costumer Need
CNC	Computer Numerical Control
CPS	Cyber-Physical System
CPPS	Cyber-Physical Production System
CS	Computer Science
DCS	Distributed Computer System
DMAIC	Define, Measure, Analyse, Improve and Control
DP	Design Parameter
DR	Design Requirements
EE	Extended Enterprises
ELI	Element of Interest

ERP	Enterprise Resource Planning
FMEA	Failure Mode and Effect Analysis
FPS	Flexible Production System
FP	Focus Point
FR	Functional Requirement
GDP	Gross Domestic Product
HCI	Human-Computer Interaction
HMI	Human Machine Interaction
HMS	Holonic (autonomous self-reliant) Manufacturing System
I4.0	Industry 4.0
ICT	Information and Communication Technologies
IMS	Intelligent Manufacturing System
IOT	Internet of Things
IIOT	Industrial Internet of Things
IT	Information Technology
JIS	Just-In-Sequence
JIT	Just-In-Time
KPI	Key Performance Indicator
LM	Lean Management
M2M	Machine to Machine (communication)
MAS	Multi Agent System
MCDM	Multi-criteria decision making
MES	Manufacturing Execution System
ML	Machine Learning
MST	Manufacturing Science and Technology
OPC UA	Object linking and embedding for Process Control Unified Architecture
PDCA	Plan-Do-Check-Act cycle
PLC	Programmable Logic Controller
PN	Production Network
PV	Process Variable

QFD	Quality Function Deployment
R&D	Research & Development
RAMI 4.0	Reference Architectural Model Industry 4.0
RFID	Radio Frequency Identification
RCS	Resilience Control System
RPS	Reconfigurable Production System
RPN	Risk Priority Number
SC	Supply Chain
SCM	Supply Chain Management
SME	Small and Medium Enterprises
SMED	Single Minute Exchange of Die
SSAC	Single Station Automated Cells
TPM	Total Productive Maintenance
TPS	Toyota Production System
UX	User Experience
VR	Virtual Reality
VSM	Value Stream Mapping
WG	Working Group
TRIZ	Theory of Inventive Problem-solving

Chapter 1.

Introduction

This chapter presents an introduction about Industry 4.0 (I4.0) and Cyber-Physical Production Systems (CPPS). It provides context on the necessity of CPPS in enterprises in order to maintain their competitiveness going forward into the I4.0 (re)evolution. It also defines and presents the research questions that drove this dissertation as well as the objectives to achieve.

1.1. Scope

The present work is submitted as a partial requirement to obtain a Master's degree in Production Engineering from Setubal School of Technology, IPS (Polytechnic Institute of Setúbal, Portugal). Its main goal is the development of a methodology designed to assist and guide enterprises in a phased and sustainable transition process into Industry 4.0 (I4.0).

Cyber-Physical Production Systems (CPPS) are widely recognized as the key to unlock the full potential benefits of I4.0. The proposed methodology was conceived to support the design, development and deployment (3D) of CPPS. Its fundamental premise is the perception that in this new industry paradigm the implementation of changes in the Technological dimension has to be accompanied simultaneously with equal changes in the Human and the Organizational dimensions of the enterprise. In accordance to these concepts the proposed methodology is appropriately named CPPS-3D.

The assumption that there is an urgent need for enterprises to evolve into I4.0 so that they can remain competitive, sustainable and achieve economic success in the global market, justifies the theme of this work and is its main motivation. The adoption of new concepts and technologies inherent to I4.0 brings many and varied challenges at the technological, organizational and human levels, which obviously implies commitments and investments. As synthesis, the desired transition is neither an intuitive process nor feasible to carry out without adequate planning.

For the development of the present dissertation’s and to drive the development work a few research questions were raised:

- What is the level of preparation of enterprises for transition into I4.0?
- What contributions can new technologies bring to enterprises?
- How can enterprises be better assisted and guided in this (re)evolution?

Based on researching and learning about the level of enterprises preparation and the contributions that new technologies can bring them, the definition of CPPS-3D methodology and the proposal of its use responds to the last question. It does so by proposing specific phases that by being sequentially developed and integrating different steps and actions, will lead enterprises and their managers towards a new industry paradigm.

1.2. Context and outcomes

At the beginning of this decade the German government promoted the development of the concept of I4.0 [1]. This concept has been globally adopted in different countries and continents, using different denominations like Industry 4.0, 4th Industrial Revolution or Digital/Smart Factory, amongst others. This represents a new global trend in production system’s organization, execution and control, and it brings to the industry many new paradigms [2]. The I4.0 with its different paradigms defends the integration of all assets such as workers, systems and products, as well as the business units of the enterprise as a way to achieve an optimized, flexible, productive and dynamic production process. For this evolution two main capabilities are essential to develop, namely automatic data collection and communication and afterwards sorting and analysis of data received. From those two capabilities higher levels of operational productivity and automatization are expected by means of transformation of the entire enterprise into an industrial process model of value adding as well as knowledge sharing and management [3].

I4.0 as a global trend is also following suit in Portugal [4]. A recent survey [5] has shown that 76,6% of Portuguese enterprises are micro, small or medium sized, 56,5% is still family-based and only 39,1% of managers from micro, small and medium-sized enterprises have an academic degree. Another recent survey [6] reveals overall productivity levels well below the European average of €44,10 of impact of each hour of work in the Gross Domestic Product (GDP) with Portugal only achieving €31,73. These aspects advocate the need to look past the Technological dimension and into the Organizational and the Human dimensions as it seems only logical to assume that enterprises are lacking in the proper skills and knowledge going towards a new age of digitalisation. As such all help in guiding enterprises is certainly much needed and also a driving force behind present motivations.

Regarding the Technological dimension, in theory and at its full technological plenitude, I4.0 will stand as an integrated, self-adaptable and self-configurable production process powered by state-of-the-art technologies, big data handling and analysis algorithms. However there are currently still many research gaps towards that goal and several challenges must yet be addressed from design, through development and to implementation. This agile and dynamic environment will only be possible by improving and enhancing the capabilities of cyber-physical systems (CPS). A CPS is the integration of computation and physical processes on a single system enabling monitoring and controlling capabilities through embedded computers and communication networks. By interlinking all CPS in the production system a Cyber-Physical Production System (CPPS) is realized [2].

The methodology proposed within this work helps enterprises through this process by offering a systematic approach to assist them in analysis and decision making. It does this by means of assessing necessities and then structuring CPS implementation across current production systems, in order to evolve into full CPPS in the long term.

CPPS implies a relationship of increasingly greater abstraction of automated processes as it evolves from the shop floor to complex computational layers. This stands as a necessity to evolve the current traditional automation pyramid into a new decentralized industrial architecture [3]. Therefore the widely accepted 5C architecture to define a CPPS evolution stages is also a major point of reference in the present work.

Regarding the Organizational dimension, it too must evolve and redefine its traditional ways in order to keep pace with the technological advancements and better deal with the aggressiveness of global markets. This means that top management should be aware of the coming changes and pre-emptively develop strategical new paths to adapt and seize new opportunities, with a focus on knowledge building, cooperation networks and promotion of employees' qualifications [7].

Regarding the Human dimension, as CPPS evolve the tendency is to relieve humans from the standard, repetitive and routine tasks, and integrate them as vital key elements in charge of handling the exceptions to take advantage of their creative thinking skills. This can only be obtained by advocating retraining and requalification of people across all enterprise levels, from shop floor to top management [8].

Taking into account these three dimensions, the proposed CPPS-3D methodology finds its support in the integration of Lean principles, methods and tools into the business culture of the enterprise, in order to promote continuous improvement, sustainability and communication. For that it follows a basic principle of cyclic phased design and implementation inspired mostly in the PDCA cycle. Throughout its stages it also proposes resorting to established quality tools such as Quality Function Deployment (QFD) or Failure Mode and Effect Analysis (FMEA), as well as design methodologies such as Axiomatic Design.

As a whole CPPS-3D consists of two main phases namely Assessment and Project Development that represent two distinct work phases, with different objectives. Each phase is built upon sequential steps to enable the necessary discussion, reflection/reasoning, decision-making and action-taking needed to further progress in the methodology. In the Assessment phase an enterprise is evaluated across all three discussed dimensions and that evaluation is then complemented with a developed visual assessment tool. In the Project Development phase it is established a sequence of tasks to successfully deploy solutions to gaps identified in the previous phase.

CPPS-3D was validated with a case study at a leading Portuguese manufacturer of metal-based solutions and products. It was used to assess the necessity of improvements at a particular production section and then design and implement an appropriate solution to identified gaps. It consisted in the realization of a new visual management system on the shop floor with remote communications capabilities. With the use of CPPS-3D methodology it was possible to conclude that once the system is fully deployed the expected benefits are faster decision-making, better production management, more accurate and reliable data availability as well as the promotion of a more dynamic workplace with improved reactivity to problems.

1.3. Structure

The dissertation is organized in five chapters, being the first chapter the present one. It provides an overview on the theme of I4.0 and contextualises the importance and timeliness of Cyber-Physical Production Systems (CPPS).

The second chapter presents the bibliographical research reviewing various aspects of the Technological, Human and Organizational dimensions of I4.0. It also features some principles, tools, and methods deemed relevant for the development of the proposed methodology.

The third chapter describes the two-phase CPPS-3D methodology. The first phase provides an assessment on current status of an enterprise towards I4.0 to identify gaps and improvement actions. The second phase intends to guide enterprises through all stages of implementing an improvement solution from design up to deployment.

In the fourth chapter it is described the application of CPPS-3D methodology to a production section in a leading Portuguese manufacturer of metal-based solutions and products. It is reported the developed work followed by discussion of observations and conclusions of this particular case study.

The fifth and final chapter presents the overall conclusions along with proposals for future work development with the aim to improve the proposed methodology and to make it a framework structure to help enterprises to evolve into I4.0, concepts, paradigms and technology.

Chapter 2.

Industry 4.0 background knowledge

This chapter presents the current state of I4.0 in regards to its Technological, Organizational and Human dimensions. Cyber-Physical Production Systems (CPPS) are introduced as a widely supported mean to evolve enterprises into I4.0. To support CPPS design, development and deployment this chapter reviews state of the art in regards to concepts, tools and methods considered relevant to the proposed methodology.

2.1. Concept and development

At the end of the 18th century industrialization started with the introduction of mechanization equipment based on water and steam power thus creating a first industrial revolution. In the 2nd half of next century electrically-powered mass production of goods based on the division of labour once again revolutionized the industrial world creating a second industrial revolution that lasted up to World War II. In the 1960s a third industrial revolution started when the advances in electronics and IT promoted ever-increasingly automation of production processes, with machines taking over a substantial proportion of the manual labour [1][2]. These industrial revolutions are summarized in Figure 2.1:

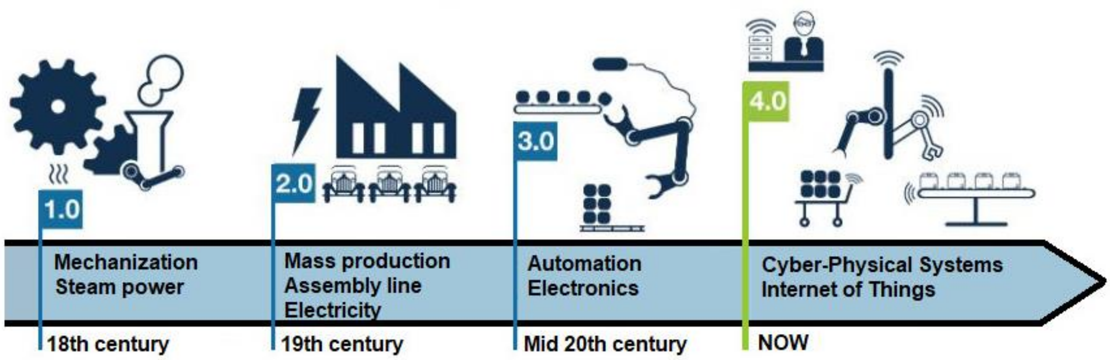


Figure 2.1 - The four stages of Industrial Revolutions (adapted from [9])

In 2011, born from a strategic government initiative, a 4th industrial revolution started to be formulated with the concept of German's "Industrie 4.0", later adopted as part of the High-Tech Strategy 2020 Action Plan for Germany. Its implementation recommendations were formulated by a group composed of 16 enterprises, 10 institutes, 2 trade unions and 4 trade associations who gathered experts in several fields to collaborate in five separate working groups (WG) [1][10]:

- WG 1: Smart Factory with Wittenstein leading Trumpf, Daimler, VDMA, ZVEI and others;
- WG 2: Real Environment with Siemens AG leading Deutsche Telekom, ABB and others;
- WG 3: Economic Environment with SAP AG leading ABB, Hewlett-Packard and others;
- WG 4: Human Beings and Work with DFKI leading BMW, Festo, VDMA, ZVEI and others;
- WG 5: Technology Factor with Bosch leading Infineon, Bitkom, TU München and others.

All WG were under the general coordination of the acatech - National Academy of Science and Engineering, and chaired by both Dr Siegfried Dais of Robert-Bosch GmbH and Prof. Henning Kagermann of acatech. In 2013 all WG concluded their work and a series of concrete recommendations was presented to Federal Chancellor Angela Merkel [1][10].

Upon conclusion of works, the "Plattform Industrie 4.0" was founded in order to coordinate Germany's efforts in evolving into the fourth industrial revolution [1][10]. Through this platform it was created the “Reference Architectural Model Industrie 4.0” (RAMI 4.0). RAMI 4.0 presented in Figure 2.2 is a 3D meta-model describing the crucial aspects of I4.0 and it facilitates the breakdown of its complex interrelations into smaller simpler clusters. With RAMI 4.0 it’s possible to design a step-by-step migration from current to future production environments [11].

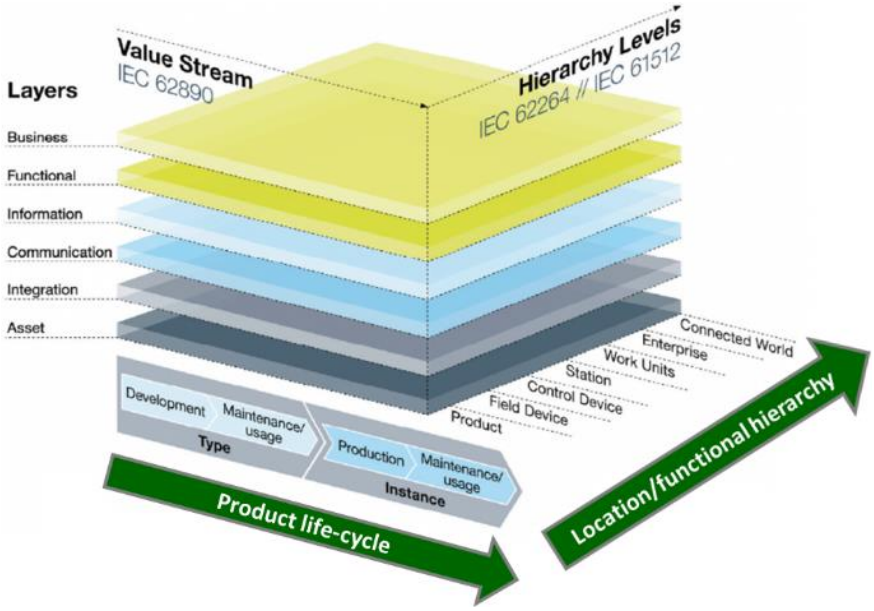


Figure 2.2 - Reference Architectural Model for I4.0 (extracted from [12])

The left horizontal Value Stream axis is based on the international standard for life cycle management IEC62890 and defines type and instance. If an idea, concept or product is in planning and not available or realized yet, it’s called a type. After design and prototyping are completed, and it’s ready for production it then becomes an instance, first in production stage and then in usage, [11][12]. The right horizontal Hierarchy Levels axis is based on the international standards series for enterprise IT and control systems IEC62264 and IEC61512. Its levels represent the different functionalities within factories or facilities starting at the product and going all the way up to the connected world [11]. The vertical Layers axis describes the full integration of every production element by decomposition into six tiered layers, [11][13]. These layers are:

- Asset Layer: represents not only physical components such as conveyor belts, PLC’s, robots, documents and connected (to the virtual world) persons, as well as non-physical components such as software and ideas.
- Integration layer: Here lies the processes of digitization of assets through tools such as sensors, RFID readers and HMI.
- Communication layer: This layer deals with the standardization of communications by use of uniformed data formats and predefined protocols.
- Information layer: In this layer happens the processing and integration of the different data received in order to turn it into useful information.

- Functional layer: To support business procedures and generate logic of automated rules and decisions this layer creates a horizontal integration platform of several functions, enabling the formal description of functions.
- Business layer: Ensuring the integrity of functions within the value stream, this layer enables the mapping of the business model and links between different business models.

RAMI4.0 represents the increasing complexity of the production system that must be worked through towards I4.0. Evolution starts by the digitalisation of assets and their consequent integration into the production system. Afterwards construction of effective communication networks enables data retrieval which results in better information availability. From this more advanced business procedures can be developed supported by automated decision-making and horizontal integration of systems. The proposed methodology follows this line of thought.

As new paradigm, I4.0 represents a new way of organizing and controlling value-adding systems (Figure 2.3). This means that it affects all areas from order management, research and development, production, commissioning, delivery up to use and recycling of produced goods. Thus all involved assets such as workers, systems, products and resources have to be integrated as smart, self-organized, cross-corporate, real-time and autonomously optimized instances [3].

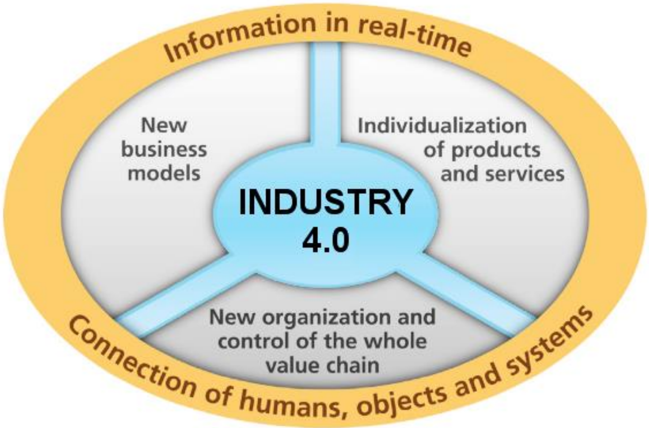


Figure 2.3 - Industry 4.0 concept (adapted from [3])

Through this integration I4.0 aims at achieving higher levels of operational efficiency, productivity and automatization, namely by becoming an industrial process model of value adding and knowledge management. Five major relevant features of I4.0 are [2] :

- Digitization, optimization and customization of production
- Automation and adaptation
- Human-Machine interaction (HMI)
- Value-added services and businesses
- Automatic data exchange and communication

Ultimately, the long term vison of I4.0 is to reach the point of [10]:

- Batch sizes of one (item individualization) at mass production prices;
- Highly flexible, more productive (up to +50%) and fewer resources (up to -50%) production, compatible with an urban environment;
- Dynamic design of business and engineering processes;
- Work-life balance of individual workers by taking account of their availability;
- Use of smart assistance systems to support older employees;
- Gradual upgrades to existing infrastructures;
- Competitive high-wage economy.

Recognizing these potential future benefits, other countries or regions in the world are following the movement started in Germany, being examples Horizon 2020 and Factories of the Future (European Union), Industrial Internet Consortium (USA), Industrial Value Chain Initiative (Japan) and Made in China 2025 (China) [14]. Through joint efforts between research institutes, universities, industries and local/national governments many are working towards innovative infrastructure implementation while simultaneously developing mid/long-term I4.0 roadmaps [15]. In 2017 reports summarized in Table 2.1, Portugal was actually considered as one of the top 24 leading competitive nations striving for I4.0.

Table 2.1- Global competitiveness rankings for I4.0 (extracted from [15])

Rank	Nation	UBS	WEF	IMD	Average
1	Singapore	2	1	1	1.3
2	Finland	4	2	4	3.3
3	U.S.A.	5	5	3	4.3
4	Netherland	3	6	6	5.0
5	Switzerland	1	7	8	5.3
	Sweden	11	3	2	5.3
7	Norway	8	4	10	7.3
8	United Kingdom	7	8	11	8.3
	Denmark	9	11	5	8.3
10	Hong Kong	7	12	7	8.7
11	Canada	15	14	9	12.7
12	New Zealand	10	17	14	13.7
13	Germany	13	15	17	15.0
14	Taiwan	16	19	12	15.7
15	Japan	12	10	27	16.3
16	Australia	17	18	15	16.7
17	Austria	18	20	16	18.0
18	Israel	21	21	13	18.3
19	**Korea**	**25**	**13**	**19**	**19.0**
20	Ireland	14	25	21	20.0
21	Belgium	19	23	22	21.3
22	France	20	24	25	23.0
23	Malaysia	22	31	24	25.7
24	Portugal	23	30	33	28.7

Within this ranking, many European countries appear at the top. Providing a better view on the European status, authors [4] researched the databases of Eurostat, the statistical office of the European Union. This research looked for variables representing concepts associated by literature to I4.0 in the universe of production enterprises with ten or more employees. Taking into consideration its results two defining factors to measuring I4.0 status in European countries were considered:

- Industry 4.0 Infrastructure: referring to the combination and simultaneous occurrence of interconnectivity, interoperability and virtualization as an indication of the ability to develop I4.0.
- Big Data Maturity: expressing the capacity to process the information generated by the I4.0 infrastructure. The ability to extract the data and interpret the information originated during the production processes and/or the supply chain processes adds value as it increases predictive power and facilitates error management.

With these in mind the factor scores for each country are graphically presented in Figure 2.4. The horizontal axis represents the first factor where countries that fall on the right of the vertical axis show a higher than average Industry 4.0 Infrastructure. The vertical axis represents the second factor where countries placed over the horizontal axis show a higher than average ability to treat information from Big Data Maturity, [4].

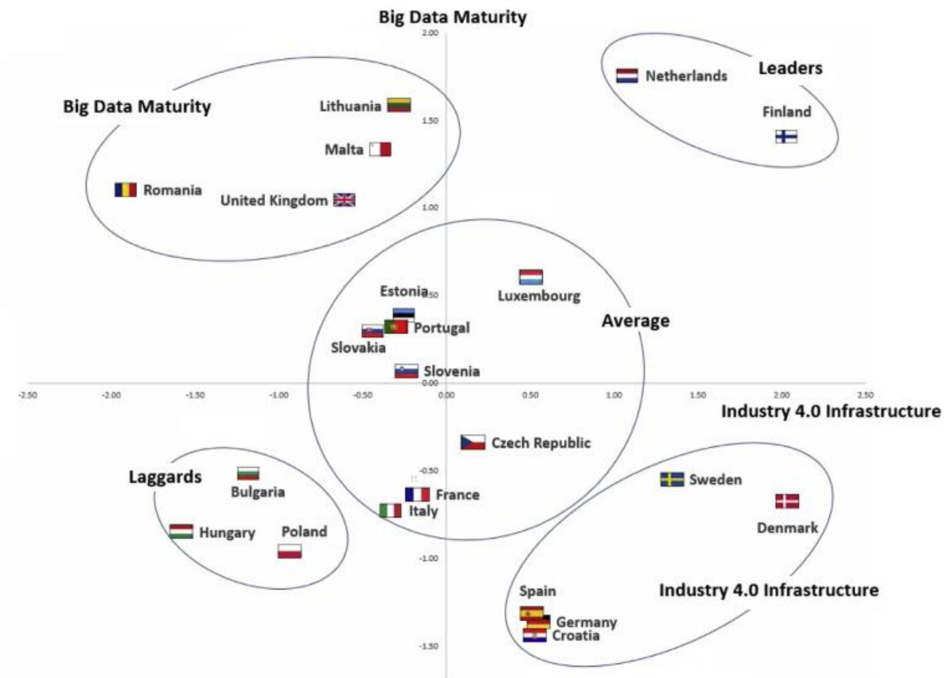


Figure 2.4 - Clusters of I4.0 status measuring in production across EU (adapted from [4])

In broader terms the horizontal axis translates into the ability to collect and transmit the data from sensors, devices and geolocation of portable devices, while the vertical axis the ability to automatically sort and analyse all data received. High I4.0 Infrastructure values signifies a country’s production sector possesses a high percentage of enterprises that combine use of communications networks with platforms and machines connected through it. Countries showing a high value of Big Data Maturity indicates the existence of technological analytical capabilities in its production sector. A high level of both dimensions supports the strong possibility of interconnectivity, interoperability, information transparency as well as virtualization, and points heavily at the possibility of advanced I4.0 existence in those countries [4].

Divided into 5 distinct clusters, Netherlands and Finland show up as leaders in both dimensions with all others trailing. Portugal is in the Average cluster, reporting a slightly better result in big data maturity than I4.0 infrastructure. This can be interpreted as Portugal having the technological capabilities to make use of data but there's the need for further research on helping enterprises identify their gaps in developing I4.0 infrastructures.

While technologically Portugal is considered in the average if it is looked at data from the Portuguese industry it is noticed that a more complex issue is probably undermining the evolution path. A survey conducted in 2016 (Figure 2.5) revealed that 76,6% of Portuguese enterprises are either micro, small or medium sized and 56.5% are held by the founders. It also revealed that in management 78.7% of top managers are also the founders or immediate family and that in micro, small and medium enterprises on average only 39,1% has completed higher education [5].

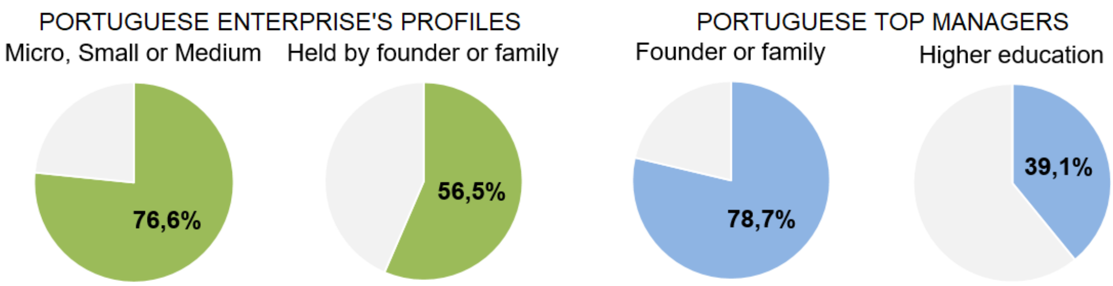


Figure 2.5 – Profile statistics of Portuguese enterprises and top managers (adapted from [6])

This means a majority of Portuguese enterprises are still family-based businesses with underqualified managers.

Additionally this is also in line with one other OECD survey. In it is revealed that in 2015 Portugal was below the European average in terms of productivity. While Ireland is presented as leading the survey in which each hour of work added €76,25 to their Gross Domestic Product (GDP), and with the European average at €44,10, in Portugal the impact of each hour of work on the GDP was only of €31,73 [6].

In accordance with these results there are strong beliefs that beyond the technological side of I4.0 evolution it will also be needed to look at the organizational side. Portugal is definitely a country where micro to medium enterprises are the most common and management may be lacking in the proper skills and knowledge to go towards a new age of digitalisation. Thus, the need for assistance and guidance is certainly a key issue and a driving force of this work.

I4.0 lets enterprises gather much more data than before. This data then needs to be processed using advanced tools (analytics and algorithms) to generate meaningful information able to provide deeper understanding of current operating conditions, faults, failures and useful insights for factory management. Ultimately, components and systems will gain self-awareness and self-predictiveness paving the way to reach just-in-time maintenance and gain near zero downtime. The key to success is providing high-end quality products/services at the lowest cost and industries are now racing to improve performance as much as possible to increase profits and reputation. However, some challenges are identified such as security breaches, data privacy, the needs for investments in new technology and the ability to retraining of workers into new skills, most notably those with repetitive and routine work [15].

In literature so far there’s no unanimously adopted definition of I4.0 in neither academia nor industry. At best it can be summarized as an integrated, adapted, optimized, service-oriented, and interoperable production process which is correlated with algorithms, big data, and high technologies, making use of Cyber-Physical Systems (CPS) to fulfil the agile and dynamic requirements of production and to improve its effectiveness and efficiency [2].

It is widely accepted that CPS will be the key for I4.0. CPS, like other I4.0 concepts, are also still evolving with several challenges needed to be addressed from design through development to deployment. This is the fundamental premise of the proposed methodology. It presents systematic approaches to assist enterprises in better assessing their necessities and then implement CPS across their current production systems in order to evolve into I4.0.

Assessing an enterprise across many I4.0 related categories isn’t easy and can be very time consuming. It is also a topic for which there’s still no global accepted consensus. Summarizing this, Table 2.2 presents maturity models for I4.0 assessments found in literature [16].

Table 2.2 - Summary of I4.0 Maturity Models (adapted from [16])

Author	Maturity Model	Dimensions	Assessment levels
Rockwell Automation (2014)	The Connected Enterprise Maturity Model	(1) Information infrastructure (2) Controls and devices (3) Networks (4) Security policies	5 levels: Assessment, Secure and upgraded network and controls, Defined and organized working data capital, Analytics, Collaboration

Author	Maturity Model	Dimensions	Assessment levels
Lichtblau et al. - IMPULS VDMA (2015)	INDUSTRIE 4.0 - READINESS	(1) Strategy and organization (2) Smart factory (3) Smart operations (4) Smart products (5) Data-driven services (6) Employees	6 levels: Outsider, Beginner, Intermediate, Experienced, Expert, Top performer
Anderl et al. - VDMA & Partners (2015)	Guideline Industrie 4.0	I4.0 Toolbox involving various characteristics and technologies	5 phases: Preparation, Analysis, Creativity, Evaluation, Implementation
Geissbauer et al. - PWC (2016)	industry 4.0: building the digital Enterprise	(1) Digital business models and customer access (2) Digitization of product and service offerings (3) Digitization and integration of vertical and horizontal value chains (4) Data & analytics as core-capability (5) Agile IT architecture (6) Compliance security, legal and tax (7) Organization employees and digital culture	4 levels: Digital novice, Vertical integrator, Horizontal collaborator, Digital champion
Schumacher et al. (2016)	A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises	(1) Strategy (2) Leadership (3) Customers (4) Products (5) Operations (6) Culture (7) People (employees) (8) Governance (9) Technology	Five-level Likert-scale for maturity (1-Not distinct to 5-Very distinct) & Four-point Likerty-scale for practical importance (1-Not important to 4-Very important)
Qin et al. (2016)	A Categorical Framework of Manufacturing for Industry 4.0 and Beyond	Nine maturity items across a two-axis matrix: (1) Automation level (2) Intelligence level	(No concrete assessment levels presented)
Ganzarain J., Errasti N. (2016)	Three stage maturity model in SME's toward industry 4.0	A three-stage maturity model: (1) Envision 4.0 (2) Enable 4.0 (3) Enact 4.0	5 levels: Initial, Managed, Defined, Transform, Detailed business model
Gökalp et al. (2017)	Industry 4.0-MM	(1) Asset management (2) Data governance (3) Application management (4) Process transformation (5) Organizational alignment	6 levels (0-5)
Akdil et al. (2017)	Maturity and Readiness Model for Industry 4.0 Strategy	(1) Smart products and services (2) Smart business processes (3) Strategy and organization	4 levels (0-3)

Author	Maturity Model	Dimensions	Assessment levels
Jung et al. (2017)	Smart Manufacturing System Readiness Assessment	(1) Organizational maturity (2) Information technology (IT) maturity (3) Performance management maturity (4) Information connectivity maturity	6 levels: Not performed, Initial, Managed, Defined, Qualitative, Optimizing
Lee et al. (2017)	A Smartness Assessment Framework for Smart Factories Using Analytic Network Process	Multi-criteria decision making (MCDM) with analytic network process (ANP) based model (29 assessment items)	5 levels: Checking, Monitoring, Control, Optimization, Autonomy
Schuh et al. - acatech (2017)	acatech Industrie 4.0 Maturity Index	(1) Resources (2) Information systems (3) Organization structure (4) Organizational culture	6 levels: Computerization, Connectivity, Visibility Transparency, Predictive capacity, Adaptability
Scremin et al. (2018)	Towards a framework for Assessing the Maturity of Manufacturing Companies in Industry 4.0 Adoption	Thirty assessment items across a three-axis matrix: (1) Strategy (2) Maturity (3) Performance	5 levels (0-4)

Apart from some (more complex) exceptions, the general approach to these maturity models consists of defining several evaluation categories across conceptual dimensions based on the RAMI 4.0. Based on this, the proposed assessment of CPPS-3D methodology chooses a broader and simpler choice of dimensions based on the belief that this will facilitate the understanding and application of it. In this sense, and across many different conceptualizations, it was found that all of them can be narrowed down to three omnipresent dimensions of I4.0, namely the Technological [17], the Human [18] and the Organizational dimensions [7].

2.2. Technological dimension

According to [19], a production system can be defined as "a collection of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts. The integrated equipment includes production machines and tools, material handling and work positioning devices, and computer systems. Human resources are required either full time or periodically to keep the system running” The production system is what adds value to parts and products.

To derive a general classification of production systems four distinguish factors are implied:

- Types of operations performed
- Number of workstations and system layout
- Level of automation
- System flexibility

Based on these, production systems can be classified in three basic types as in Figure 2.6. Each type can be implemented either as fully manned, as fully automated or a combination of both [19]:

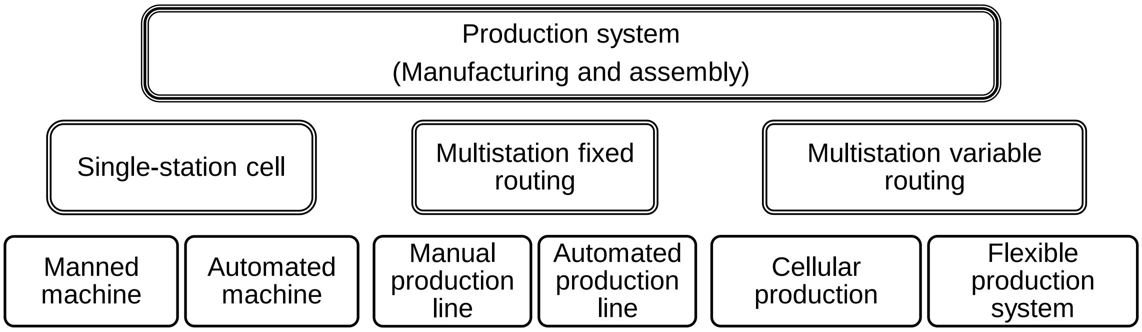


Figure 2.6 - Classification of production systems (adapted from [19])

Starting from these basic production systems and since I4.0 is mostly discussed on the digital level of production, the following are proposed as fundamental I4.0 production systems:

- Single-station automated cells (SSAC): Machines are attended by workers no more than one machine cycle, decreasing labour cost and increasing productivity relative to manned cells. Used for constant product batches, these cells are typically made up of a cluster of automated machines (or just a single machine) and an automated loading/unloading system by robots, conveyors, etc. A common example is a CNC machine centre system with a feeding system/robot for loading and unloading, [19]
- Automated assembly system (AAS): Automatic handling, usually robots, and feeding systems that replace workers leading into increased production, automated safety monitoring and quality control. AAS is a fixed assembly system, designed to manufacture a specific high demand product in a fixed order of assembly without change of product design during production. Common applications for AAS are sheet metal forming and cutting, rolling mill operations and spot welding [19]
- Flexible production system (FPS): Having flexibility as its core feature, in the FPS several workstations and an automated transport feeder system are controlled by means of a distributed computer system (DCS). During the whole production cycle, every workpiece is identified enabling immediate process changes as required, quick responsiveness for changeovers, improved material utilization with a small number

of workers, and reduction of inventory requirements. However, despite its name, this system is designed for specific part families and is not completely flexible. It's a common system found in machining applications, such as milling and drilling [19]

- Computer-integrated production system (CIPS): A CIPS uses computers to control all functions of a completely automated production system, which implies a full factory level automation design, including materials management, production lines and distribution. Also, cooperative automation, more rapid and less error response from production as well as information exchange by at least two integrated computers are defining characteristics of a CIPS [20]
- Reconfigurable production system (RPS): The RPS differs from the FPS as it aims at increasing the changing response of different requirements focusing more on customization flexibility rather than the production flexibility of the FPS. A RPS is typically characterized by the capabilities of modularity, integrability, customization, convertibility and scalability. RPS requires reconfigurable machine tools, reconfigurable inspections machines and material transport system [21]

Researching the current technological status of these five fundamental systems the technological gaps between current production systems and the plenitude of I4.0 can be estimated as in Figure 2.7 [20].

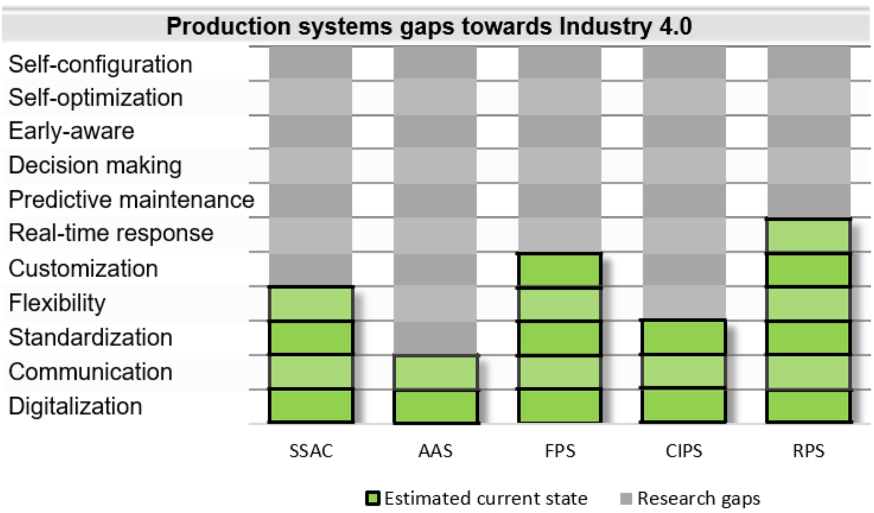


Figure 2.7 - Estimation of current research gaps towards I4.0 (adapted from[20])

RMS is estimated to currently being the most advanced in terms of developed I4.0 concepts but there are still many large gaps that need to be fulfilled to reach the full capacities of I4.0. To close these gaps, all of these systems still need to achieve intelligent concepts for which there's still currently no easy path [13] and are dependent on ongoing developments of computer science (CS), information and communication technologies (ICT) and manufacturing science and technology (MST) [1].

Historically through time there has always been a concurrent development of CS and ICT with MST by means of an interplay between virtual and physical world's technologies. Looking at Figure 2.8 a corresponding advancement of technologies can be inferred that represents how there's a simultaneous evolution and continuous convergence of all [3].

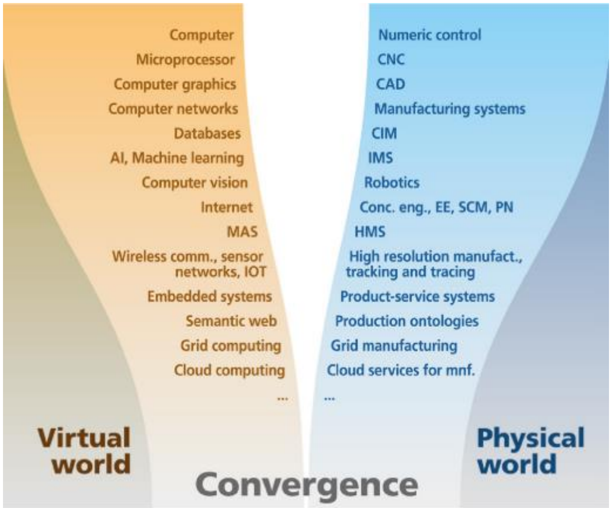


Figure 2.8 - Convergence of virtual world and physical world technologies (extracted from [3])

The advancements of CS and ICT (on the left) lead to the development of MST (on the right) which then present newer challenges to the former due to its importance and highly complex nature. In this way of both worlds is clear. Numeric control of machine tools developed from computers advancements, CNC machines evolved with the microprocessor and CAD systems appeared from the application of computer graphics. The creation of computer networks made possible the development of production systems and databases allowed the storage of Computer Integrated Manufacturing (CIM) data. Intelligent Manufacturing Systems (IMS) were created from advances in artificial intelligence (AI) and machine learning (ML) and recognition of environments and objects by robots was made possible by computer vision algorithms. The coming of the internet as a worldwide accessible technology revolutionized the cooperation of both humans and systems, and the areas of concurrent engineering (CE), extended enterprises (EE), supply chains (SC) and production networks (PN). Multi-agent systems (MAS) were necessary to accomplish agent-based production and Holonic Manufacturing systems (HMS) comprised of autonomous and cooperative building blocks of a production system. Wireless communication, sensor networks and Internet of Things (IOT) enabled high resolution production as well as tracking and tracing solutions. Embedded systems allowed for the implementation of smart automation solutions and product-service systems. Semantic web solutions supported the interoperability in production by use of ontologies, i.e. formal definitions of products, to limit their complexity and organize their related characteristics more efficiently. In a similar way, grid and cloud computing built the foundations of their counterparts in production.

This convergence of technologies points the way to the emergence of Cyber-Physical Systems (CPS), systems where physical and software components are deeply intertwined enabling the incorporation of machinery, warehousing systems and production facilities in global business networks, [1]. To realize this intertwining, in I4.0 there are nine key group technologies and tools widely accepted as its building blocks (Figure 2.9) [22].

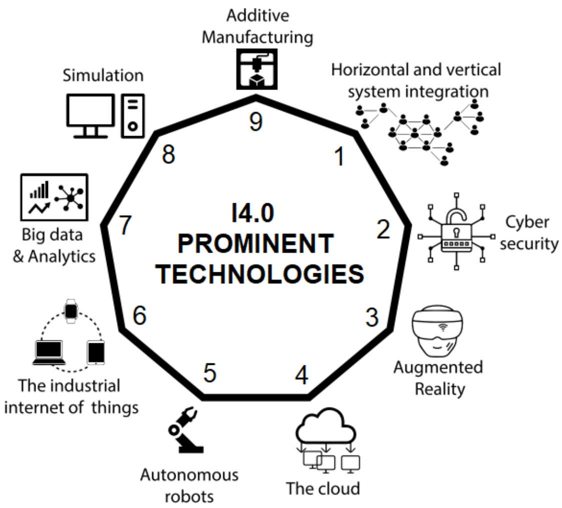


Figure 2.9 - Group technologies and tools for industry 4.0 (adapted from [22])

Widely agreed upon, depending on application and purpose, a CPS can resort to any or all of these enabling technologies and tools to fulfil its requirements [13][22]:

(1) Horizontal and Vertical System Integration: Enable real time data sharing by the integration of all systems, creating a collaborative scenario between engineering, production, suppliers, marketing, and supply chain operations, taking into account different levels of automation and information flow.

(2) Cyber-security: The problematic of cyber security is an emerging and complex subject because, by having connected objects generating and distributing information through networks, systems need to be shielded from vulnerabilities that can lead to others accessing confidential data.

(3) Augmented Reality: The use of intelligent devices to superimpose virtual elements into physical reality allows for increased human performance by supplying information and procedures to the user in a given situation or environment.

(4) The cloud: A mechanism of information storing and sharing, with the ability of worldwide availability anytime, anywhere, provided there's internet access, allowing monitoring and control of physical processes through digital platforms.

(5) Autonomous robots: Use of autonomous robots reduces errors in simple tasks, increases efficiency of production lines and optimizes production.

(6) Industrial Internet of Things (IIOT): Enables the flow of information from devices and sensors through centralized controllers that report data about equipment, components, products, services and processes both in the enterprise and throughout the supply chain.

(7) Big data and analytics: All productive processes generate data so its coherent organization and analysis generates added-value as it allows information to be correctly processed, analysed and transmitted to the decision makers, leading to the optimization of production processes, quality and service.

(8) Simulation: Saving time and resources, it allows to evaluate changes in the configuration of machines, process flow and plant designs, testing decision's effectiveness before their implementation.

(9) Additive Manufacturing (AM): 3D printing and prototyping allows for process creation visualisation, proof of design concepts and small samples without wasting production materials, which in turn that translates to lower design and production costs.

In a production environment, depending on application and purpose, any single CPS will be constructed resorting to these technologies and tools. It can then be linked to another CPS handling a different application. By interlinking all CPS in the production environment, a Cyber-Physical Production System (CPPS) is created [13].

2.2.1. Cyber-Physical Production System

Formally, a CPS can be defined as the integration of computation and physical processes, in which embedded computers and networks will monitor and control physical processes, most commonly by means of feedback loops making possible for physical processes to affect computations and vice versa [23]. By interlinking all CPS in the production system a Cyber-Physical Production System (CPPS) is realized. A CPPS is a system that comprises smart machines, storage systems and production facilities, able to autonomously exchange information, trigger actions and control each other independently. CPPS facilitates improvements to the industrial processes involved in production, engineering, supply chain management, material usage and life cycle management [1].

This is exemplified in Figure 2.10 representing shop floor integration. Through use of adequate enabling technologies each production element gains CPS-capability effectively becoming a unique CPS in its own [24].

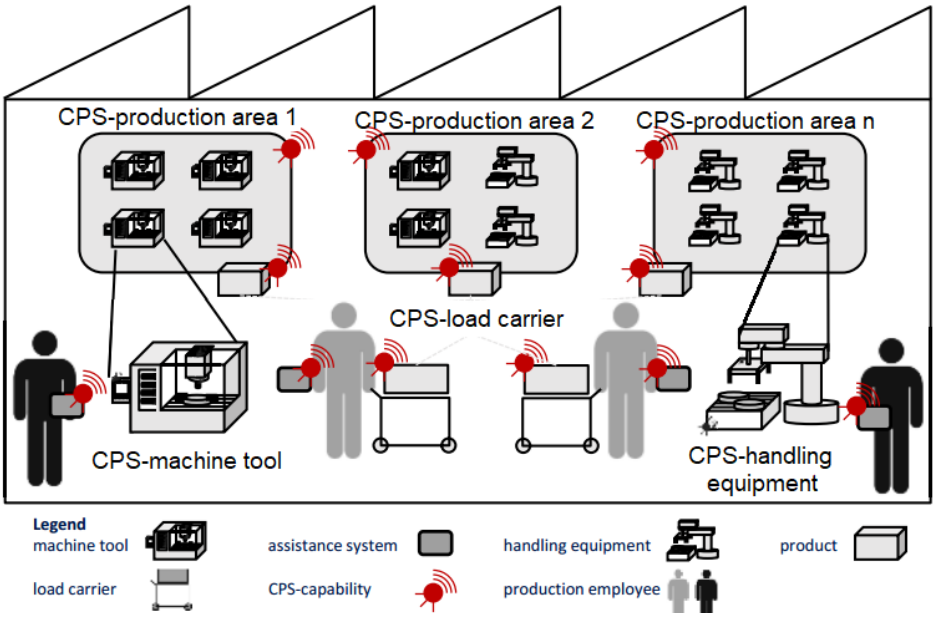


Figure 2.10 - Scenario of a cyber-physical production system (adapted from [24])

With every unit integrated into the production systems, each CPS can then autonomously collect and send its own data, as well as receive information as needed, thus forming a base physical connection layer. Full system integration is then built creating two other essential layers, the middleware and the computational layers. Figure 2.11 represents this [25].

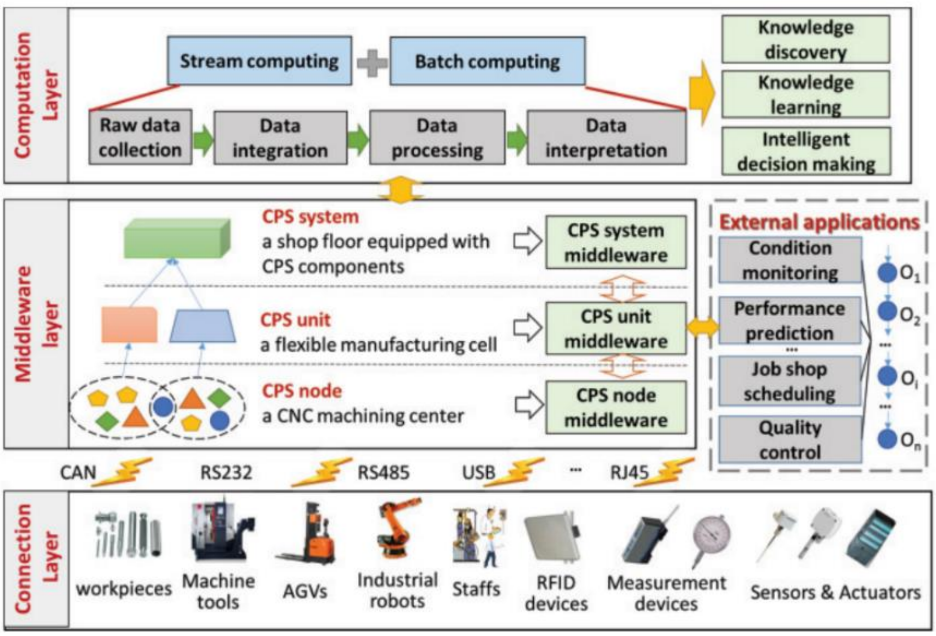


Figure 2.11 - CPPS layers (extracted from [25])

- Physical connection layer: The first step in building a CPPS starts in the shop floor by embedding components such as sensors, RFIDs and other measurement devices in production resources. The choice of these components must take into account operational issues such as protocol, processing, location, distance and storage. Groups of machines can be connected with each other through fieldbus or industrial Ethernet. This layer deals with collecting and transmitting operational data [25].
- Middleware layer: This layer interfaces the other two existing layers by filtering superfluous data and creating a uniform data format and data exchange standard necessary for information to flow both ways. It must deal with issues such as receiving variable data formats from most likely the use of different brands and types of embedded components and correctly translate production commands given by the computation layer or external applications [25].
- Computational layer: For this layer specific models, algorithms and tools must be developed to analyse and extract underlying patterns from all received data. This will provide a better insight over machine working conditions, workpiece quality, production processes, etc. Here two forms of big data computing need to be addressed, namely batch computing to process large volumes of historical data, and stream computing to process near real time shop floor data. The conjunction of these, along with human experience, creates a supervisory unified view of data, information and knowledge which supports intelligent decision-making and is then transmitted back to the shop floor for operation/process control and maintenance [25].

CPPS is the link between field level mechatronics and cloud-based systems. Figure 2.12 presents some examples of applications in the transition process from mechatronic systems level to cloud-based, highlighting in the horizontal-axis the necessary fields of knowledge as the level of abstraction from the physical world goes up [26]:

At the mechatronic level, processes and procedures are well defined and understood, as the integration and interconnection of mechanical engineering, electrical engineering and automation amongst others form the basis for the physical design of a range of products and product types. At CPS level, as systems become more complex, the relationship between actual physical components and users becomes more complex, being primarily defined by function. At cloud-based level systems are many defined by their greater level of abstraction where many of its constituents are unknown to the system builder other than in terms of their contribution and function in the overall system [26].

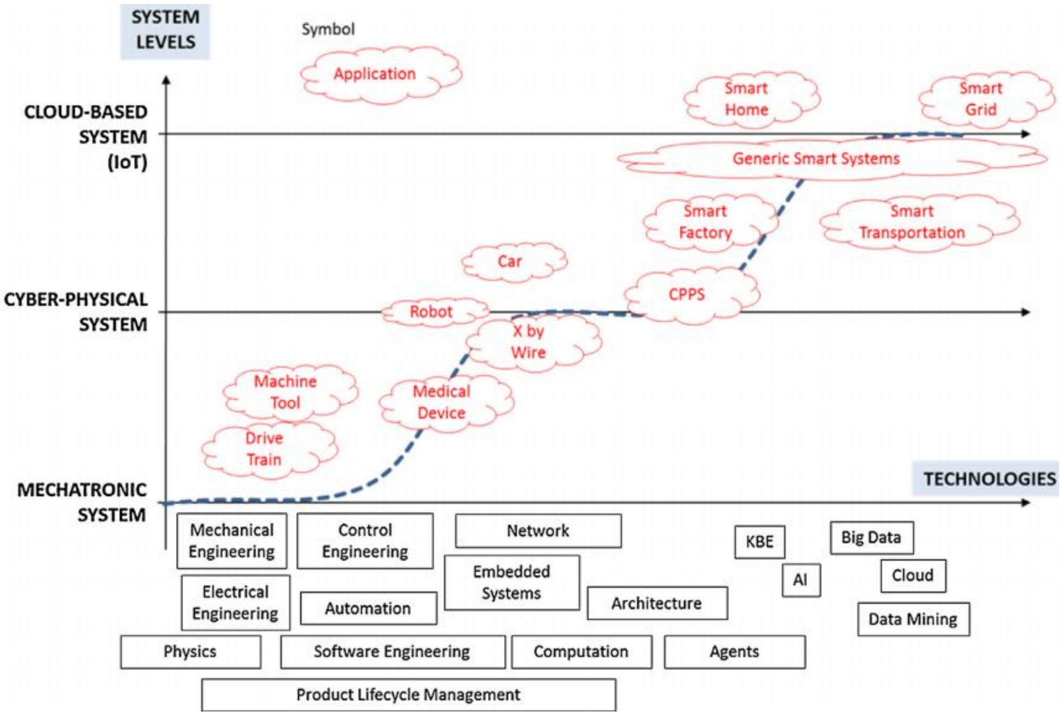


Figure 2.12 - Transition process from Mechatronics to IoT (extracted from [26])

A clear relationship of increasing abstraction is possible to discern going from mechatronics up to cloud-level. This concept is represented in Figure 2.13.

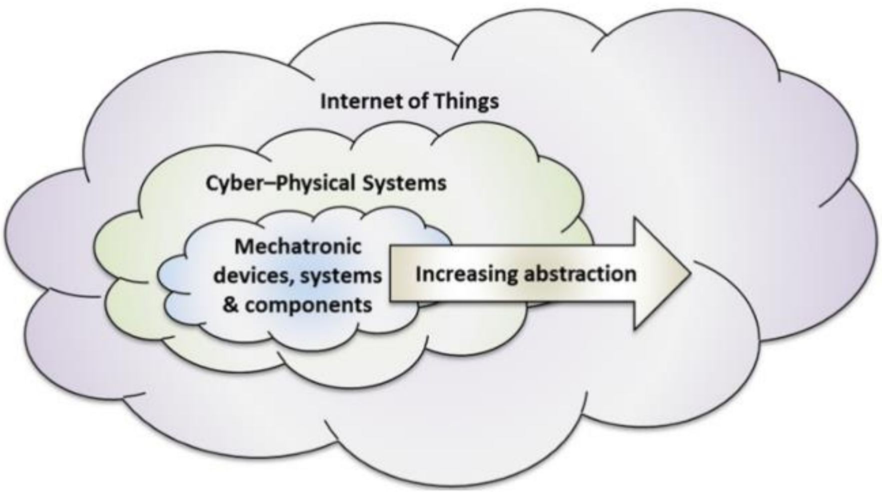


Figure 2.13 - Relationships of increasing abstraction (extracted from [26])

To fully integrate physical and cyber systems the traditional automation pyramid (left side of Figure 2.14) needs to evolve into a new form of industrial architecture in order to realise a new decentralized paradigm (right side of Figure 2.14) and the becoming of CPPS [3].

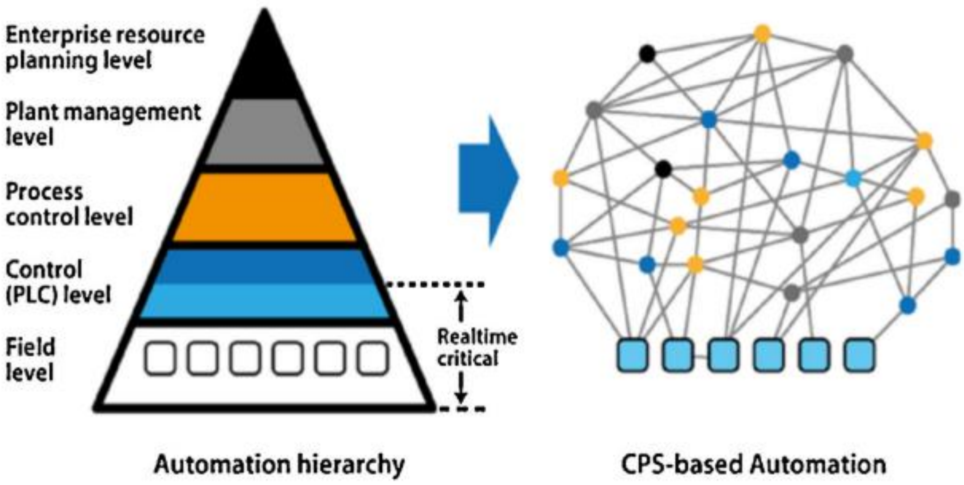


Figure 2.14 – Evolution of automation hierarchy to CPS-based automation (extracted from [3])

CPS-based automation keeps the typical control and field levels of the pyramid ("Real-time critical") as base of the new paradigm. At this base level Programmable Logic Controllers (PLC) control the critical field processes ensuring the highest performance for control loops in real-time. Then at higher levels of hierarchy the pyramid ceases to exist and gives way to a more decentralized way of functioning, a defining characteristic of CPPS. In this way only two main functional levels of CPPS exist. The lower one is responsible for the advanced connectivity ensuring real-time data acquisition from the physical world and information feedback from the cyber space. The upper one incorporates intelligent data management, analytics and decentralized computational capabilities constructing the cyber space [3].

To realise this, [27] proposes the 5C architecture, a guideline for developing and deploying a CPPS by defining a five level sequential workflow to construct such system from the initial data acquisition, to analytics, to the final value creation. The 5C architecture consists of five levels:

- Level I – Smart Connection level: Representing the foundation stage of data acquisition this first step of building a CPPS consists in finding the best ways to gather accurate and reliable data from machines and their components. For this, data can be directly measured by sensors, obtained from controllers or accessed from enterprise management software such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES) or Supply Chain Management (SCM) There are however two very important factors at this stage to be taken into account, which are, first the selection of proper sensors (type and specifications) for each application, and second, given the possibly very diverse type of data to collect, the choice of appropriate and specific communication protocols for data acquisition and transfer to servers [27].

- Level II – Data to information Conversion level: With data collected, statistical tools and algorithms can be used for converting said data into useful information. Through this information better analysis can then be carried out [27].
- Level III - Cyber level: This is the central information hub of the 5C architecture. The previous level pushes all gathered information into here from all the connected machines enabling the formation of an interconnected production network. With massive information collected, specific analytics must be developed and used to provide insight of individual machines and create the ability for self-comparison, where every single machine's performance can be compared with others in the network. Additionally historical information can be used to evaluate current machine performance and predict future behaviours [27].
- Level IV – Cognition level: Here CPPS generates thorough knowledge of the monitored system to present to expert users enabling and supporting decision-making on priority of tasks to optimize processes and systems. For the presentation of information, special care must be taken here in the creation of proper infographics to completely transfer acquired knowledge to users and decision makers [27].
- Level V – Configuration level: Providing the feedback from cyber space to physical space, at this level systems act as supervisory control to make machines self-configure and self-adaptive, acting as a resilience control system (RCS) to apply preventive and corrective decisions [27]. A resilient control system can be defined as one that maintains state awareness and an accepted level of operational normalcy in response to disturbances, including threats of unexpected or malicious nature [28].

These concepts of the 5C architecture are summarized in Figure 2.15.

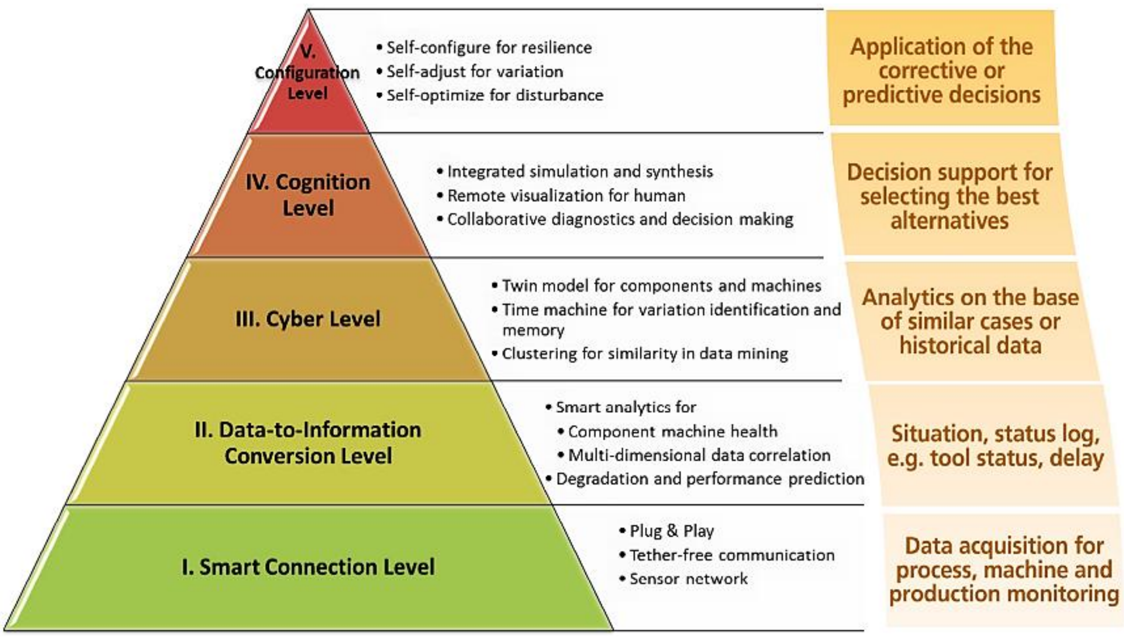


Figure 2.15 - 5C architecture for implementation of CPPS (adapted from [3] [27])

With this approach in CPPS design, the base *Smart Connection* level represents the physical space, the intermediate levels represent the transition into cyber space and the top C*onfiguration* level represents the realization of feedback from the cyber back to the physical space [3].

To evolve into CPPS, individual CPS must be developed first. CPS dissemination will greatly contribute to the ongoing evolution of I4.0 by promoting the proliferation of advanced technologies as well as innovative information and communication systems [29].

Many challenges still lie on how to implement CPS to drive I4.0 since no clear path seems to be yet defined. In addition this transition can become very costly hence the dilemma, in particular for smaller enterprises, whether investments made can produce real benefits. This fact is aligned with the purpose and supports the main motivation for this dissertation which is the proposition of a methodology to assist enterprises in this (re)evolution. Furthermore bringing in new technologies has its effects in two other dimensions inside the enterprise, namely the Human and the Organizational dimensions. For the former it means that workers roles must be re-evaluated for new functions. As for the latter, management will be presented with new challenges while trying to keep up with the technological evolution and deciding on where, how and when to invest. The following topics will address these other two important dimensions.

2.3. Human dimension

In the past, it was envisioned a completely automated factory that operated without any human intervention but with the advent of I4.0 that was deemed neither realistic nor desirable because of technological and economic reasons. Substantial benefits to I4.0 can be reaped from an improved human–machine interaction based on sophisticated assistance systems and collaborative machines. This means that the human dimension is an absolutely fundamental key aspect of I4.0 [7].

With much research towards full automation the transition to I4.0 brings significant changes to the human workplace. Humans can provide governance, agility and resilience to complicated issues. Humans have the ability to undertake complex operations, perform flexible movements and the ingenuity to solve problems in the face of sparse or missing data. Moreover knowledge exchange and reciprocal learning is promoted by interaction of human and CPPS during problem-solving processes. As such humans are still seen as crucial elements, unlikely to ever be replaced entirely within production systems and are therefore a fundamental part of I4.0 [30].

CPPS purpose is also to substitute humans in the standard and routine decision situations. Humans will then be reintegrated into the CPPS to be in charge of the tasks of understanding, interpreting, evaluating, verifying and deciding on the validity of all generated information. In this sense, considering as essential aspects both human qualifications and CPPS autonomy [18] propose the optimal collaboration matrix illustrated in Figure 2.16:

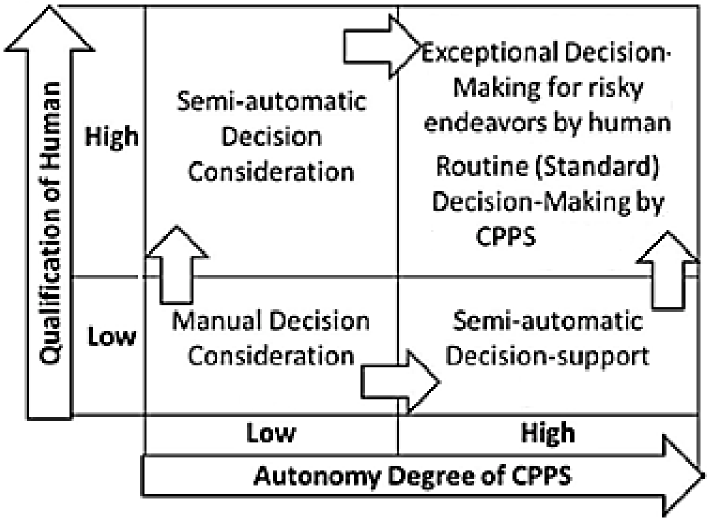


Figure 2.16 - Matrix for optimal collaboration of Human and CPPS (adapted from [18])

Following suggested directions, optimal collaboration between human and CPPS is only obtained with both high qualification of humans and high autonomy degree of CPPS. Four matrix zones are identified according to the combination of human qualification level and CPPS autonomy degree as follows [18]:

- Low-Low: Manual decision consideration through analysis of a problem space and identification of decision alternatives.
- Low-High: Semi-automatic decision supported by deployment of advanced assistance and recommendation systems.
- High-Low: Semi-automatic decision consideration by highly qualified personnel through analysis of information and notifications provided by information systems.
- High-High: The optimal collaboration scenario is achieved in the right-upper quadrant with exceptional decision-making by humans and routine decision-making by CPPS. The first relates to supervised decision-making in risky endeavours as for example acquiring new machines. The second relates to automatic decision-making in regards to low risk and non-sensitive endeavours such as shifting maintenance milestones.

Therefore to advance through the zones there is a technological need to create artificial intelligence algorithms and software solutions to increase CPPS levels as well as a simultaneous organizational imperative to establish work based learning mechanisms for human training towards new job roles. Only this way it will be possible to transition to the ideal state of collaboration between highly qualified personnel and highly autonomous CPPS [18].

Since I4.0 is still developing, humans, the most flexible production system of all, still don’t have a clear definition of their role in the (re)evolution. Based on the 5C architecture (Figure 2.15) authors [8] propose a complementary implementation of an unified architecture between human, product, process and production environment as illustrated in Figure 2.17, named Cyber-Human Systems (CHS):

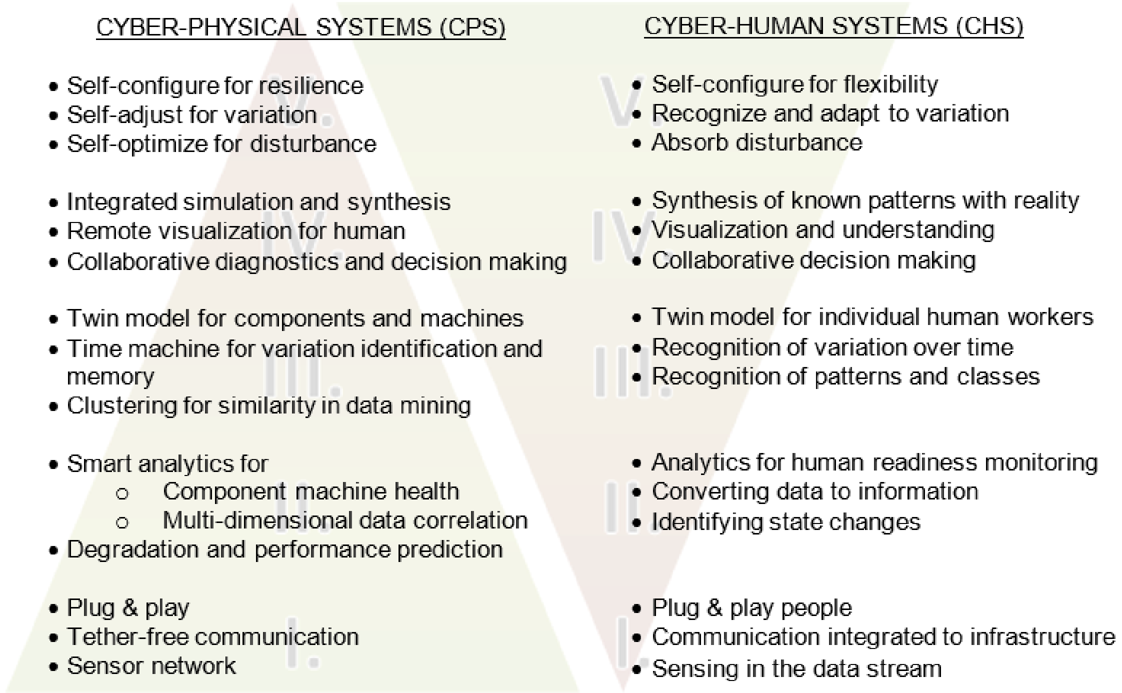


Figure 2.17 – Complementary 5C architecture for Cyber Human Systems (adapted from [8])

This unified vision of future smart production facilities aims for a deeper control and visibility of manual processes through all generated data and resultant information, something not previously accessible. It allows also a deeper understanding of the dynamics of human in the production loop by enabling omnipresent data used for workforce competences development and monitoring the working conditions, in terms of health and safety. The use of an inverted pyramid represents that the activities deemed difficult to implement in the cyber world are the very ones that humans perform naturally, and vice versa. The characteristics and challenges of each level are the following [8]:

- Level I - Smart connection level: CHS need to identify and implement methods of acquiring accurate and reliable data from humans and their surroundings with careful sensor selection and seamless tether-free methods to manage data acquisition and transfer. Human variability, human privacy, ethical data usage/storage and acceptance of the emotional requirements of instrumenting a human are sensible issues that must be considered and are recurring challenges, not only at this level but also along the entire length of the pyramid.
- Level II - Data-to-information conversion level: CHS systems will have its focus on human health monitoring to diagnose, advise and prevent unsafe/non-value added activities

such as continuously checking human body orientations to warn if activity deviates too far/often from ergonomic safe zones. These systems will also be able to gather information about inherent qualities of human workers.

- Level III - Cyber level: Similar to the corresponding CPS level, CHS here aggregate data for systematic comparisons between singular workers either on individual processes or facility wide. This data is then used for running analytics for past, current and future worker performance, and suggest possible improvements back to the human worker who can self-adapt its performance on the fly.
- Level IV - Cognition level: Taking advantages of human expert analysis and higher-level understanding of the system as a whole CHS at this level support knowledge driven decision making and optimizations.
- Level V - Configuration level: Human workers have an inherent intelligence that can be naturally leveraged for resilient, self-adaptive, preventive and corrective actions. CHS at this level acts as the exceptional and supervisory control of all decisions made in previous levels to ensure their correct implementation or the need for corrective/adaptive actions.

In conclusion, the human dimension is an indispensable factor of I4.0. As CPPS take charge of routine tasks and decisions humans will be left with the vital roles of handling the exceptions, the complex issues and identifying causes for production variability. For this retraining and requalification of human workers at all levels is critical. And for that to happen changes on an organizational dimension will also have to happen, which is the next topic.

2.4. Organizational dimension

The organizational dimension is very much related with functions, responsibilities and principles as well as methods and tools implemented and used to run and manage an enterprise, keeping its competitiveness and sustainability. As the transition to I4.0 is worldwide ongoing and gaining heavy momentum an enterprise’s management should be attentive to the coming changes and develop strategies to grasp and seize new advantageous opportunities. On the business level, to identify and prioritize such opportunities managers can look for costs reductions and productivity increases in eight key areas [31][32]:

- Resource/process: Costs can be reduced by reducing energy and material’s consumption and revenues increased by achieving faster speeds and better yields (more products through compliance check).
- Asset utilisation: Every minute a machine isn’t producing is lost revenue. Maximizing machine’s flexibility and decreasing planned/unplanned machine downtime and changeover times with predictive maintenance are important.
- Labour: Productivity is gained by reduction of waiting times and increase of speed of workers’ operations by reduction of tasks’ complexity.

- Inventories: Too much inventory ties up capital, leading to high capital costs. Accurate data can be used to reduce excess inventory caused by inaccurate stock numbers, unreliable demand planning that requires bigger safety stock, or overproduction.
- Quality: Improving quality brings value since scrap and products requiring rework lead to extra costs. Detecting and eliminating inefficiencies like unstable processes in production, deficient packaging in the supply chain or distribution and unskilled installation can create value.
- Supply/demand match: Profits can be maximized by having perfect information and understanding of customer demand not only of quantities but also of the features customers are willing to pay for.
- Time to market: Concurrent engineering or rapid experimentation/prototyping helps reach the market with a new product earlier creating additional value through increased revenues and potential early-mover advantages. Better data can lead to faster improvements on product design and production.
- Service/aftersales: Gathering information on product utilization and lifecycle allows to offer the customer better and faster solutions when problems occurs.

With I4.0 promising benefits across all these areas it's important to discern the most efficient paths for a sustainable evolution. Building on this by means of academic and corporate literature reviews, authors [7] created a framework consisting of eighteen management challenges for going into I4.0 across six different categories as in Figure 2.18.

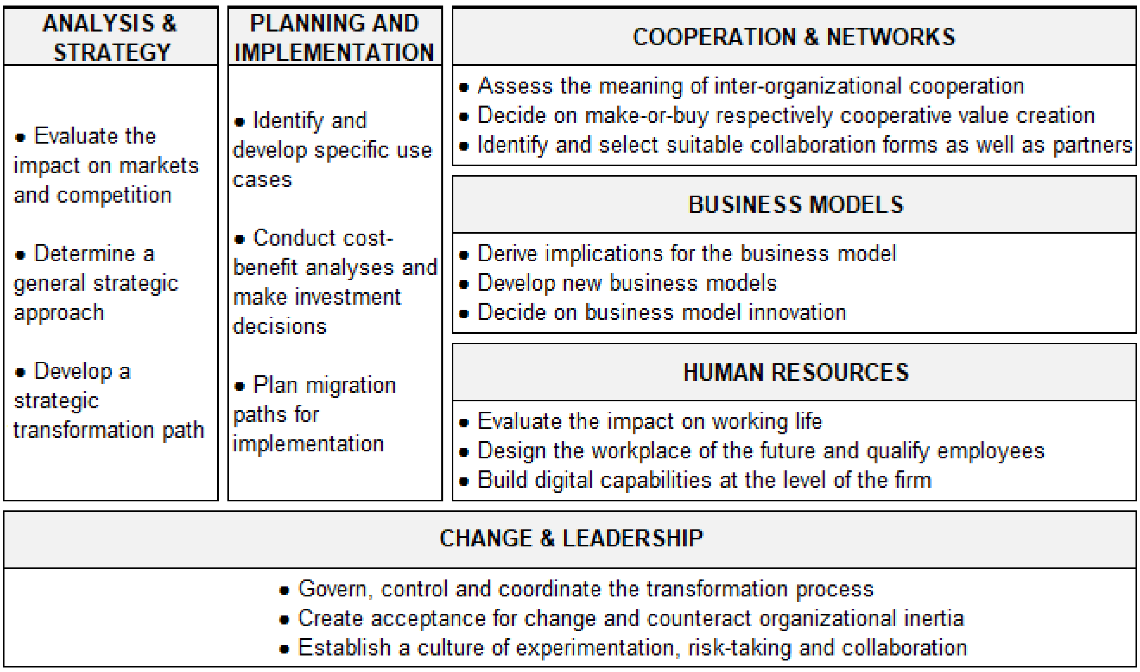


Figure 2.18 - Framework for management challenges on I4.0 (adapted from [7])

Each category's challenges are [7]:

- Analysis and strategy:
    - Evaluate the impact on markets and competition to understand essential drivers of change, anticipate possible impacts and define market boundaries, rules of competition, power relations and the disruptive potential of I4.0.
    - Determine a general strategic approach to define whether the enterprise acts as a creative innovator, a fast adaptor or an observant laggard, i.e., decisions must be made on the risks the enterprise is willing to take.
    - Develop a strategic transformation path by deconstructing complex transformations into simpler manageable evolution phases.
- Planning and implementation:
    - Identify and develop specific use cases by means of applying I4.0 technologies to specific projects, initiatives and implementations aiming to improve a particular machine or process.
    - Conduct cost–benefit analyses and make investment decisions based on estimating costs and future added value taking into consideration both monetary and non-monetary (networking) effects as decision support.
    - Plan migration paths for implementation and integration of new technologies and systems into the existing infrastructure without replacing or short-term depreciating assets, nor interfering with already perfectly functioning workflows.
- Cooperation and networks:
    - Assess the meaning of inter-organizational collaboration by developing awareness of risks and benefits of a strengthened enterprise with respect to cooperation and networks.
    - Decide on make-or-buy respectively cooperative value creation by evaluating and determining which activities should be done internally, which should be pursued cooperatively or which should be outsourced.
    - Identify and select suitable collaboration forms as well as partners by seeking ways to build knowledge through collaboration opportunities (innovation clusters, production networks, strategic partnerships, specific suppliers, etc.)
- Business models:
    - Derive implications for the business model starting by understanding the general characteristics and influencing factors that trigger business model innovation in I4.0, thus enabling adaptation and improvement of one's own business model.
    - Develop new business models by identifying the technological possibilities and drivers of I4.0 that can be taken advantage of to create new business models or add changes to the current one.
    - Decide on business model innovation evaluating whether adaptations are necessary and to what extent, such as just complementing an existing one or instead readapt and completely replace an outdated one.

- Human resources:
    - Evaluate the impact on working life by pursuing comprehension of I4.0 implications on the working world and the necessary redefinition of the human role in it, allowing to anticipate how task range, depth and content may change.
    - Design the workplace of the future and qualify employees by determining the new necessary competences and abilities to integrate workers in I4.0 and using this knowledge to train and qualify them.
    - Build digital capabilities at the level of the firm by looking at all three dimensions (technological, human and organizational) as source of data and information that adds value to the enterprise.
- Change and leadership:
    - Govern, control and coordinate the transformation process by planning and defining approaches for management transition (central/decentralized and top-down/bottom-up), specific responsibilities assignments and overall change process leadership.
    - Create acceptance for change and counteract organizational inertia to overcome scepticism and fear of change from executives to managers to workers in order to motivate everybody at all levels to actively shape and participate in the transformation.
    - Establish a culture of experimentation, risk-taking and collaboration by stimulating participation in new experiments, such as pilot projects, that require multiple areas cooperation (such as electrical, mechanical and software).

From this review it was inferred that it is essential that enterprises begin to establish strategic transformation paths to better pave their ways into I4.0. Enterprises not only need to seize the advantages of new technological advancements but also develop the organizational structure to support such advancements. This means establishing the means to build knowledge, both internally and externally, to seek inter-organizational collaboration opportunities and to redefine their business model if necessary. For all this to happen leaders have to promote these changes, creating acceptance for change and counteracting organizational inertia, while simultaneously designing the workplace of the future, through qualification and motivation of employees.

In conclusion, to support I4.0 implementation and inherently CPPS it was seen that it also must be taken into account the Technological, the Human and the Organizational dimensions as these are inseparable. Further progressing in the research, it was found that one other topic deals with all three dimensions and is deeply related with I4.0, the Lean Management (LM) philosophy.

A lean environment is an easier foundation for the transition as automation and digitalization of streamlined and waste-free processes will be quicker and more efficient. In this way LM can be considered as a prerequisite for I4.0. But the reverse is also possible and beneficial because I4.0 has the tools for more accurate data collection, allowing for better informed decisions and more optimal Lean practices [33].

So being mutually beneficial their coexistence, LM with its philosophy behind, supported by proven principles, methods and tools is of great importance in the I4.0 (re)evolution. It contributes by preparing processes and defining better implementation paths while at the same time gains optimization of its own practices. Due to this, the next topic will approach the LM as an important synergy on the enterprise's evolution into the I4.0 and the starting point of background knowledge supporting the proposed methodology.

2.5. Background knowledge supporting methodology design and proposal

To support the development of the proposed methodology it was investigated philosophies and methodologies whose principles, methods and tools were aligned with CPPS development and in consideration of all three dimensions, namely Technological, Organizational and Human.

2.5.1. Lean management

Historically, the achievements of Lean Management began with the automobile industry. In the post-World War II, American engineer and statistician William Edwards Deming developed a statistical improvements model. Within the Marshall Plan, an economical program to aid Western Europe and Asia economical rebuilds, Deming introduced his model to several Japanese companies. Amongst them, one particular Japanese car manufacturer, Toyota, adopted, developed and eventually built a whole culture around it that later became known as the Toyota Production System (TPS) [34].

A characteristic of the TPS is knowledge-sharing which is believed to lead into lower costs due to technology proliferation. Another characteristic is continuous improvement promotion to mitigate the effects of process by others because in the time a competitor takes to implement a copy of shared production processes, TPS will have improved and retained the advantage. This will happen because others will be lagging in processes and be spending time and resources on implementing known processes instead of time and resources on innovations [35].

The philosophy of knowledge-sharing and continuous improvement grew stronger and eventually ended up acting as a precursor to what is today commonly known as Lean philosophy. Its principles can be applied not only to production itself but also to management as essentially an approach to running the entire enterprise. Therefore the more global concept of Lean Management (LM) is particularly relevant as it looks at the Technological, Human and Organizational dimensions of running an enterprise.

To fulfil its fundamental premise LM integrates a set of methods and tools with management principles that together aim at eliminating the identified seven forms of waste ("Muda" in

Japanese) and generate profit through cost reduction. Waste is defined as everything that doesn’t create value. The classical seven forms of waste are [36]:

- Overproduction
- Waiting for work
- Transport
- Extra work (over processing)
- Inventory
- Motion (referred to human and layout)
- Defects

Waste can be defined as anything other than the minimum amount of equipment, material, parts, space and worker's time, essentials to adding value to the product. Amongst many other interpretations, value can be perceived as what the customer is willing to pay for. Activities that do not contribute to value are waste, either total waste or temporarily necessary non-value adding. Complementing these classical forms and offering new perspectives on root-causes of wastes, [37] proposes some new forms of waste interesting to look at from the I4.0 point of view:

- Worthless products: it doesn’t matter how efficient and optimized production is if the final product doesn’t correspond to what the customer needs or wants. Hence it is absolutely critical to be able to listen to customers to correctly identify their needs and expectations, so that these can be sorted and prioritized in terms of importance. By means of this, understanding the so called voice of the customer, a valued product is obtained. This is of particular importance for I4.0 that strives for production processes flexibility that enable product customization.
- Untapped human potential: To fully create awareness of an enterprise’s own human potential both-ways communication is required between workers and management. It is essential to promote a culture of trust and mutual interest from all involved so that all relevant skills available in the enterprise are identified. This can include, amongst others, seeking past experiences of others, listening to advices from those who fully understand the processes in loco, talking to the ones in charge of fabricating it and training workers without fear of eventually losing them. Identifying these hidden worker skills potentiates the Human dimension as people can be assigned to functions where they excel.
- Excessive information: In I4.0 data collection is the basis but effective sorting through this data to form useful information is key. Only the relevant information to a user must reach that user otherwise information overload can hinder decision-makers in correctly understanding problems or workers in perceiving their roles. Selecting and prioritising what is transmitted to who and in what form must be clearly defined beforehand. In addition, this further expands its concept to management areas where common wasteful procedures can be avoided such as emails global forwarding, unnecessary team briefings or training workers for tasks they never or rarely do.

- Time: The waste of time is one that management in particular can greatly reduce by careful planning. Considering two dimensions for classifying needed activities, these can be deemed either important and/or urgent (Figure 2.19).

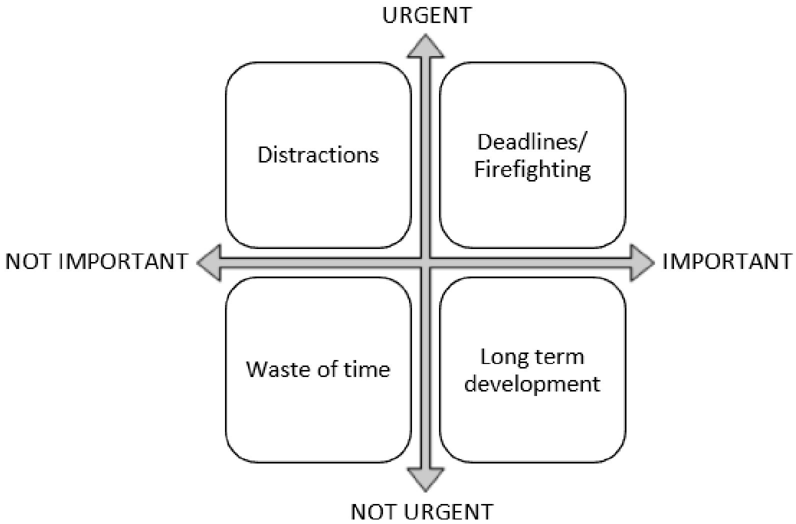


Figure 2.19 - Forms of waste of Time (adapted from[37])

On one end, important and urgent activities are crucial deadlines or out of control conditions (Deadlines/Firefighting) and must be dealt with immediately, although if these are recurring they're maybe a sign of bad management as time is heavily wasted dealing with them. On the other end, activities that are deemed not important nor urgent always exist and appropriate minimal time should be planned to address and eliminate them, but other than that are also usually considered waste of time. In between, the urgent but not important activities should be seen as Distractions and resolved quickly in order to be able to allocate more time with planning and executing the important but not urgent activities that allow for Long term development. Ideally activities that promote long tem development should be the focus and top priority of the enterprise.

- Inappropriate systems: Considering that the lean philosophy implies waste removal before automating processes this type of waste is particularly relevant. It refers not only to computers and automation systems on the shop floor but also other systems at management level that deal with things such as paperwork, communications or information analysis. New hardware, software or other physical systems should be pondered if they are really necessary, if the benefits outweigh the costs and what the enterprise can gain from them.
- Energy: This waste refers to all sources of power such as electricity, gas or oil and relates directly to the basic principles of LM. Besides the socially responsible attitude of using such resources wisely they are also a big part of the costs of operating expenses of an enterprise. In acquiring new devices proper time should be dedicated to investigate on

power efficiency and actual life to ensure long term savings. And while automatic energy management systems help, the human factor is also essential in the reduction of this type of waste. Workers must be sensitized to waste awareness and trained to acquire habits of good practices such as shutting down machines, computers, printers, turn off lights and air conditioners or use efficient routes for transports.

- Natural resources: To explain this form of waste, water and paper are the most obvious examples. The enterprise should create awareness and ways to reduce consumption of both water and paper as this is not only environmentally responsible but also reduces operational costs. Expanding the concept into I4.0, studying a product's life cycle can generate profits by considering alternative materials and resources usage for design, manufacture, customer use and recycling.
- Asymmetry in processes: Waste of time and money can easily be generated through having unevenness of operations in the production system. A levelled production scheduling should be determined by managers to respond to consumer demand favouring a pull system, much like as in fighting the waste of overproduction. In a pull system operations are based on actual market demand while in the traditional push system operations are based on demand predictions. Additionally the pace of work is worthy of particular attention to provide workers with a steady calm pace of functions instead of more prejudicial high stress moments followed by waiting periods. In these regard CPPS can be a great asset as it will not only assist decision-makers in their resolutions but also ultimately decide autonomously the most efficient way of running processes based on real time data.
- No upkeep: The definition of this type of waste derives from the philosophy of continuous improvement. Activities have to be followed through, monitored, controlled and continuously worked on. Waste reductions can translate into significant cost reductions and benefits for the enterprise but for this to happen further actions are usually necessary to maintain its benefits. Reducing wastes is an everyday effort that requires discipline and commitment to pursue all the time otherwise the resources used to achieve it in the first place will be in vain and themselves a waste.
- Knowledge: Deeply connected with the purpose of I4.0 of becoming an industrial process model based on knowledge, letting gained knowledge simply disappear from the enterprise is a very big form of waste. Gained experience and knowledge from product design, manufacture, marketing and recycling when recorded and kept in tangible forms permits that processes don't have to be relearned every time. In addition, special care must be dedicated to write down important workers' relevant know-how so that if a person leaves its functions their acquired knowledge still remains in the enterprise.

LM implies that the focus should be on the organisation as a whole before considering the individual parts. This will avoid the common issue of solving one problem only for another one to emerge because of that. With it, mistakes are seen as opportunities to improve rather than something that needs monitoring and punishing. It is accordingly a philosophy of continuous learning resting upon two pillars, namely honest self-reflection (Hansei in Japanese) and continuous improvement (Kaizen in Japanese) [37].

Consequently for LM principles and tools to be implemented, used and be effective, LM has to be integrated in the business culture by leadership and coaching to improve processes every day [36].LM is an enabler towards I4.0 mainly because having standardized, transparent and reproducible processes is of fundamental significance for introducing I4.0. Additionally LM competences are required for considering customer value alongside identifying and avoiding wastes. Lastly reducing both product and processes' complexity enables for efficient and economic use of I4.0 tools [38].

However LM and I4.0 implementations aren't necessarily a purely sequential process. They can influence each other iteratively as lean processes can be stabilized and refined by applying I4.0 tools, e.g. by means of providing data as real-time feedback to improve transparency and information quality. So a correlation exists between both as they can coexist and support each other. With general literature agreement on the compatibility of LM and I4.0 similarities can be found between both paradigms. Reduction of complexity, central pillars, and lean principles are a common ground, both are managed in a decentralized way distributing responsibility in subsystems and both focus on a pivotal role of employees [38]. These common aspects are illustrated in Figure 2.20:

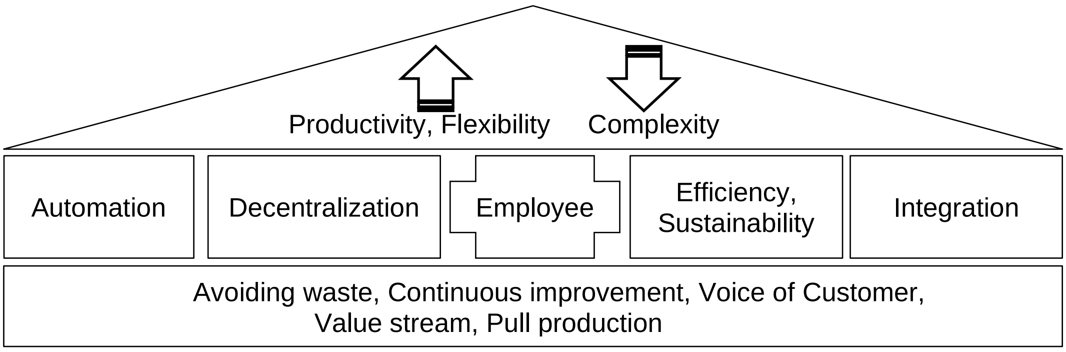


Figure 2.20 - Commonalities of LM and I4.0 (adapted from [38])

With all these commonalities it's relevant to look at their synergy. Building on a limited study by [36], authors [38] identified eight specific lean concepts, principles, methods and tools and thirteen I4.0 tools based on reviewing academic and corporate publications. Afterwards in accordance to said literature and reasonable assessment of the authors, synergy potentials between LM and I4.0 were analysed (Figure 2.21). This assessment intended to exemplify how I4.0 tools that enable the design of CPPS can contribute to further optimize the identified lean principles, methods and tools.

I4.0 \ LEAN	JIT/ JIS	Hei- junka	Kanban	VSM	TPM			SMED	VM			Poka- yoke
					1*	2**	3***		5 S	Zoning	Andon	
Additive manufacturing (AM)	x					x		x				
Plug and play							x	x				
Automated guided vehicles (AGV)	x		x									
Human-computer interaction (HCI)			x	x	x				x	x	x	x
Virtual representation (e.g. VR, AR)	x				x			x	x	x		x
Intelligent bins	x		x									
Auto-ID	x		x	x	x			x	x	x		x
Digital object memory	x				x			x				x
Digital twin/simulation	x	x	x	x		x	x	x	x			
Cloud computing	x			x	x	x						x
Real-time computing	x	x	x	x	x	x	x	x	x	x	x	x
Big data & data analytics	x	x	x	x		x						x
Machine learning				x	x			x				x

* autonomous maintenance, ** planned maintenance, *** early product and equipment management

Figure 2.21 - Synergy between I4.0 and Lean (adapted from [38])

Just-in-time/Just-in-Service (JIT/JIS) concept and principle is all about delivering the right product, at the right time, place and quality in the right quantity for the right costs. In accordance several tools can be of valuable contribution to these aims. For instances, Automated Guided Vehicles (AGV) can automatically transport anything necessary within the material flow minimizing human mistakes as well as empty trips. Complying with requirements, material can be supplied to workstations with the AGV system rerouting vehicle to alternative paths when necessary to avoid delays. Another contribution from developing CPS capabilities in the production system elements is the creation of intelligent bins and smart products where a digital object stores every necessary production parameter. This will enable a self-organization of the system that helps build robust logistics networks. The use of Auto-ID technologies, such as RFID, can be used to track and localise any object precisely reducing search time, correct part identification and continuous stock monitoring. Also, the use of big data and data analytics techniques provides the opportunity to analyse detailed real-time process information providing further knowledge about parameters, trends, and optimal decision rules. Overall these technologies and tools will allow for JIT/JIS to achieve higher transparency, shorter lead times, improved flexibility and an improved resistance against disturbances [38].

Heijunka method aims to level the production to a constant rate so that the wastes of overproduction asymmetry are reduced by solely producing the necessary costumer demand. In regards to I4.0 tools, big data and data analytics technologies can help production management. Using data history in combination with market analysis of customer's needs, planning can be further optimized and stabilized by decision makers. At the ideal CPPS goal, production planning is done automatically based on product specification, structure of the technological process, assets availability and actual demand, reducing levelling efforts and allowing for smooth short-dated adjustments [38].

Kanban, the Japanese word for signboard, is a technique aiming for continuous material flow by maintaining predefined stocks levels that guarantee an uninterrupted supply of material. Amongst other I4.0 tools, Kanban can benefit from digital twin (real time virtual model) and simulation. A digital twin allows for Kanban loops to be planned ahead virtually with more foresight leading to later be seamlessly integrated into the existing production environment. Simulation provides better insights at ideal Kanban parameters in e.g. lot size, stock, delivery frequency. Also Auto-ID technologies, increases transparency of material movements, constant monitoring of work in process and removal of unnecessary stock. Furthermore AGV use can translate into refills arriving in the exact moment when new material is required. This way material supply at shop floor level can be realized by using only a one container-system instead of the more traditional closed-loop three-bin system (at shop floor, inventory and supplier). With all this, by integrating I4.0 tools into Kanban stock levels are minimized, transparency is increased and costs are reduced. Additionally reduced inventory simplifies the detection of bottlenecks and causes of problems can be quicker identified [38].

Value stream mapping (VSM) is intended to enhance the transparency of information flow within the value creation chain, in order to better identify sources of waste, shorten lead time and facilitate production flow (Figure 2.22). CPPS expedites VSM by creation of an interconnected production environment of (near) real-time data transmission. Objects are tracked by Auto-ID and process information consolidated with big data and data analytics, leading to more accurate and reliable Key Performance Indicators (KPI) to support decision-making [38]. Typical KPI in VSM are presented in Figure 2.22 and include process time (PT), operation time (PT), process quality (PQ) and overall equipment effectiveness (OEE). CPS can help further realize waste reduction by enabling more target oriented KPIs [39].

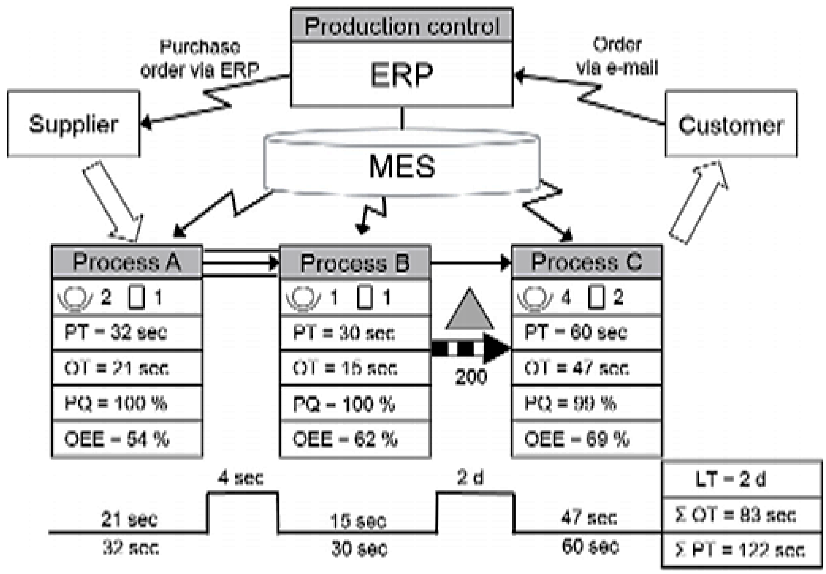


Figure 2.22 - Simplified VSM with process and value stream KPI (extracted from [39])

Additionally Human-Computer interaction (HCI) devices such as smartphones, tablets and head mounted displays allow to receive information, trigger actions, control processes, do maintenance analysis or pursue process optimization depending on user's access privileges. It is therefore a tool suitable for daily operations management, supporting continuous improvement by means of better transparency through real-time display of value streams helping waste identification and leading to value creation. Also, data analytics as well as machine learning can support VSM design and validation before implementation [38].

Referring back to Figure 2.21 implementing I4.0 inevitably results in an increasing number of maintenance objects of rising technical complexity so the Total Productive Maintenance (TPM) concept can be split into three areas. Autonomous maintenance shifts routine maintenance responsibilities from technicians to operators, planned maintenance is achieved by preventive measures executed by now freed maintenance technicians and early product and equipment management is related operations necessary to production start-ups (introduction of new products and realization of short ramp up periods). In the first area, for operators to take charge several I4.0 tools exist, with VR and AR being the most beneficial allowing for better training, instructions and visual guidance in dealing with problems. In the second area, recurring to CPS to realize smart products allows for monitoring of load, wear and defects in real-time which when cross-linked with big data and data analytics leads to more accurate defects prediction and probability. Finally in the third area, plug and play allows the autonomous integration of a technical system based on modular designs and standardized interfaces. Also digital twins contribute to fast start-up curves and realistic simulation of production plants, e.g. PLC code testing [38].

Single minute exchange of die (SMED) method aims at reducing downtime and cost caused by setup processes, facilitating small lot sizes, short lead times and low level of stock. Some obvious benefits are use of plug and play technologies to facilitate integration of new systems and AR to guide workers. Furthermore Additive Manufacturing (AM) is also expected to help reduce setup time by enabling production of varying work pieces with minimum setup times [38].

Still referring back to Figure 2.21, the purpose of visual management (VM) principles is to enhance transparency so deviations can be detected early. This is achieved by transferring targets, standards and specifications into a visual representation. VM can be implemented by 5S, zoning and Andon methods [38].

5S stands for Sort, Straighten, Shine, Standardize and Sustain, [40]. It is a workplace organization systematic approach aiming to keep it clean with all tools arranged in a reasonable way. For this Auto-ID through RFID tagging supports tool identification and instructions with reduced search time. AR may complement or even replace physical shadow boards as virtual elements guide operators on where to store tools,[38].

Zoning allows marking destinations by using visual means, such as paths, cells and departments, usually with utilisation of different colours for increased information value. Use of

HCI and AR can supress the necessity for additional physical signs and tapes by enabling navigation based on already existent natural markers like warning signs [38].

Andon, the Japanese word for lamp, is applied for visualizing status and disruptions in production and thus supports the lean principle of Jidoka. Jidoka is essentially automation with human intelligence, providing machines and operators the ability to detect when an abnormal condition has occurred and immediately stop work [40]. HCI can make use of devices like tablets, smartphones, head-mounted displays and smart watches to instantly send targeted notifications in real-time regardless of the location of the recipient. Additionally, Andon boards are used to display actual and target values in order to reveal deviations. CPS enable the collection of much more diversified data so digital Andon boards can be a solution to visualise complex data and processes in real-time (e.g. machine condition, production progress, status of orders and capacity utilization). Plus, mobile devices support access to this information anytime and anywhere [38].

Poka-yoke technique describes mechanisms that help operators to avoid mistakes. It aims to prevent defective products exiting production by detection and elimination of abnormal conditions. It is either realized by generating forced sequences or by reviewing the process during its execution and stopping it in the event of errors. Looking at I4.0 tools, Auto-ID and digital object memory (i.e. lifespan event register) grant the benefits of ensuring correct identification and assignment, avoiding incorrect deliveries and the adding of value to defective parts. In conjunction with AR it can be used to achieve zero-error picking. Ultimately and ideally, through machine learning machines will even be able to automatically adjust to irregularities to ensure optimal product quality [38].

In sum, the perspective gained from LM literature review is that it is of great interest to understand the link and synergy between LM and I4.0. LM is seen by a large majority of authors as a prerequisite to I4.0 and thus considered to be a good starting point to drive the enterprise (re)evolution for I4.0. Implementing LM already obliges to take into account the human and the organizational dimensions of the enterprise and in doing so it further prepares the whole for the upcoming challenges of dealing with the new and innovative paradigms introduced by the technological dimension. Following this line of though, to achieve I4.0, enterprises will inevitably need to conjugate the development of all three dimensions at all times. So in transitioning toward CPPS, management will definitely need tools to better support decision-making towards necessities and risks of implementing changes.

While LM represents a management philosophy set on continuous improvement and waste minimization, its many different tools are also commonly associated with Six Sigma. Sharing some of the tools and resorting to others, Six Sigma differs from LM as it is essentially a project management methodology with a defined phased sequence, goals and dates. It aims directly at improving output quality by variation reduction and minimizing causes of defects. For the value of its project management workflow the Six Sigma methodology will be looked at next.

2.5.2. Six Sigma and DMAIC methodology

Following the idea of phased design and implementation is Six Sigma. This methodology is a project development tool with a start and an end. Six Sigma drives its projects by use of the five phases Define, Measure, Analyse, Improve and Control (DMAIC) approach summarized in Table 2.3. Each Six Sigma project has defined start and end dates, as well as proposed measurable objectives to achieve, [41].

The first phase is Define and at this stage the project team is chosen and customer requirements as well as the quantifiable project objectives are identified. In the second phase, Measure the current state of the problem is mapped. Next in the Analyse phase the root causes are identified and validated. With the root causes identified, in the next Improve phase actions to correct those are discussed, implemented and validated. Finally in the last phase Control, proper tools are implemented to assure surveillance and sustainability of the actions taken.

Table 2.3 - DMAIC phases and tools

PHASES	OBJECTIVES	ACTIVITIES	TOOLS
Define	Identification of problems	• Identification of critical customers' requirements • Identification of objectives and goals • Selection of project and team • Development of implementation plan	• QFD • Benchmarking
Measure	Measurement of problems	• Mapping of the process and calculation of the process's long-term capability	• Control charts • Pareto diagrams • Histogram
Analyse	Identification of root causes	• Collection of data to identify and validate root cause of variability in processes	• Cause and Effect diagram • FMEA
Improve	Validation of results	• Selection of long-term improvement actions	• 5M (Machine, Method, Material, Manpower, Measurement) • Brainstorming
Control	Development of surveillance plans	• Implementation of control tools to ensure long-term sustainability	• Poka-Yoke • Definition of KPIs • Process documentation

Six Sigma fundamental objective is the satisfaction of customer requirements while minimising wasted resources and increasing profits. Although it is a methodology that has yielded interesting results for large enterprises, in small and medium enterprises (SME) its implementation can be more challenging considering that these usually have tighter financial constraints and less data to work with. While Six Sigma is intended to be implemented by certified experts resulting in high implementation costs it is still possible to benefit from it by adapting its model to facilitate its integration in SMEs with fewer resources [41].

This is useful because it provides a foundation concept of a project management design based on defining sequential phases, objectives and activities with possible tools of interest to use in each corresponding phase.

Looking at the proposed tools by Six Sigma, two of them are of particular interest and complement each other well in the context of CPPS design and implementation. The first is Quality Function Deployment (QFD) that enables to identify appropriate automation necessities. The second is Failure Mode and Effect Analysis (FMEA) that can determine the associated risks with a chosen option [42]. These tools will be reviewed next.

2.5.3. Quality Function Deployment

Quality Function Deployment (QFD) is a product development technique that attempts to translate costumer needs (CN) into design requirements (DR). Being of customer-driven nature it ensures that the voice of customers is implemented into the final product. Dating back its origin to the early 1970s, QFD over the years has been widely studied and found applications in the most various fields, such as product design and development, quality planning and management, production, services and education. By means of a relationship matrix during design/planning phases named the house of quality represented in Figure 2.23 it aims at converting the customer needs/requirements into technical or engineering requirements [43].

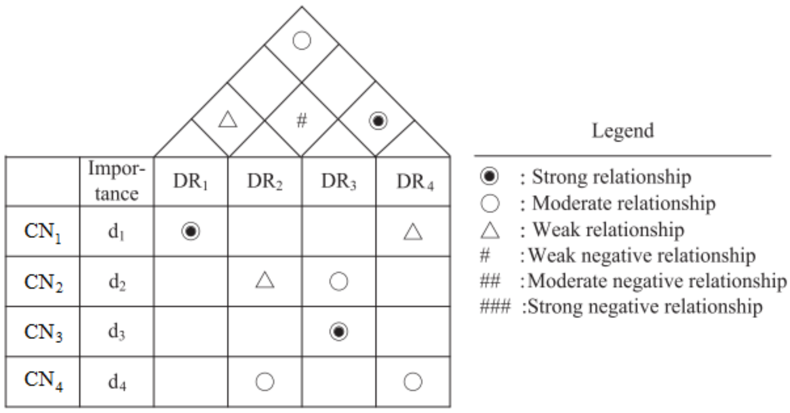


Figure 2.23 - Basic configuration of a House of Quality (adapted from [43])

The house of quality expresses the relational intensity between each pair of CN and DR indicating how a DR impacts a corresponding CN's performance. The roof of the house is a triangular-shaped relationship matrix that establishes a technical correlation between each pair of DRs. After identifying CNs and corresponding DRs the design team quantifies the priority of DRs by means of applying ratings to the information contained in the house. This is then used as a reference to financial resources allocation to achieve the best customer satisfaction as the more important DRs are identified and prioritized [43].

2.5.4. Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) is a systematic method of identifying and preventing product and process problems before they occur. Ideally FMEA is conducted in the design and development phases but it can also be executed later for improvements. FMEA aims at preventing problems before they occur thus reducing costs, enhancing safety and increasing customer satisfaction. Its objective is to look for all of the ways a process or product can fail, [44].

A failure is perceived as when the product does not perform as it should, malfunctions or even when it induces its user to use it in a wrong way. Failure modes are the ways in which a product or process can fail. Each failure mode has a potential effect with some of these more likely to occur than others. Additionally each potential effect has a relative risk associated with it. FMEA identifies these failures, effects and risks and works towards their reduction or elimination. For this it uses three factors, on a scale of 1 to 10 (low to high), [44]:

- Severity: The consequence of the failure should it occur.
- Occurrence: The probability or frequency of the failure occurring.
- Detection: The probability of failure detection before the impact of the effect occurs

By multiplying these factors (severity x occurrence x detection) the Risk Priority Number (RPN) is determined in a range from 1 to 1000 for each failure. The failure mode with the highest RPN should be attended to first. In addition special care must be dedicated to high severity rankings (9 and 10) regardless of RPN. The RPN thus ranks the needs for corrective actions. After a corrective action the failure must be re-evaluated to determine its new RPN until this reaches an acceptable value, [44]. Figure 2.24 illustrates a blank FMEA worksheet.

Failure Mode and Effects Analysis Worksheet

Process or Product: ______	FMEA Number: ______
FMEA Team: ______	FMEA Date: (Original) ______
Team Leader: ______	(Revised) ______
	Page: 1 of 1

	FMEA Process													Action Results				
Line	Component and Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Severity	Occurrence	Detection	RPN
1																	
2																	
3																	

Figure 2.24 - Blank FMEA worksheet (adapted from [44])

All FMEA projects are team based, with individuals from different areas, to bring a variety of perspectives and experiences to a specific project. These teams usually consist of 4 to 6 people from areas such as production, engineering, maintenance, materials or technical service [44].

Further continuing on the topic of quality tools and looking back at the suggested ones by Six Sigma, others are also of importance and worth referencing, namely the seven basic tools of quality.

2.5.5. Seven basic tools of quality

The seven basic tools of quality can help enterprises improve their processes by providing the means to understand them. These tools summarized in Figure 2.25 are the following [45]:

- Cause and effect diagram (a.k.a. Ishikawa or fishbone chart): a diagram that allows to identify the many possible causes of a problem and sort ideas into categories
- Flowcharts: a diagram depicting process flow allowing to understand complex processes.
- Check sheets: a prepared and structured document for collecting data
- Pareto diagrams: a graph that presents which factors are more significant
- Histogram: a graph to determine frequency distributions, i.e. how often a different value in a set of data occurs
- Scatter diagram: a 2D graph that pairs two variables, one in each axis, allowing to observe relationships between them
- Control chart: a graph used to observe how a process runs and if its measured variables stay inside defined limits

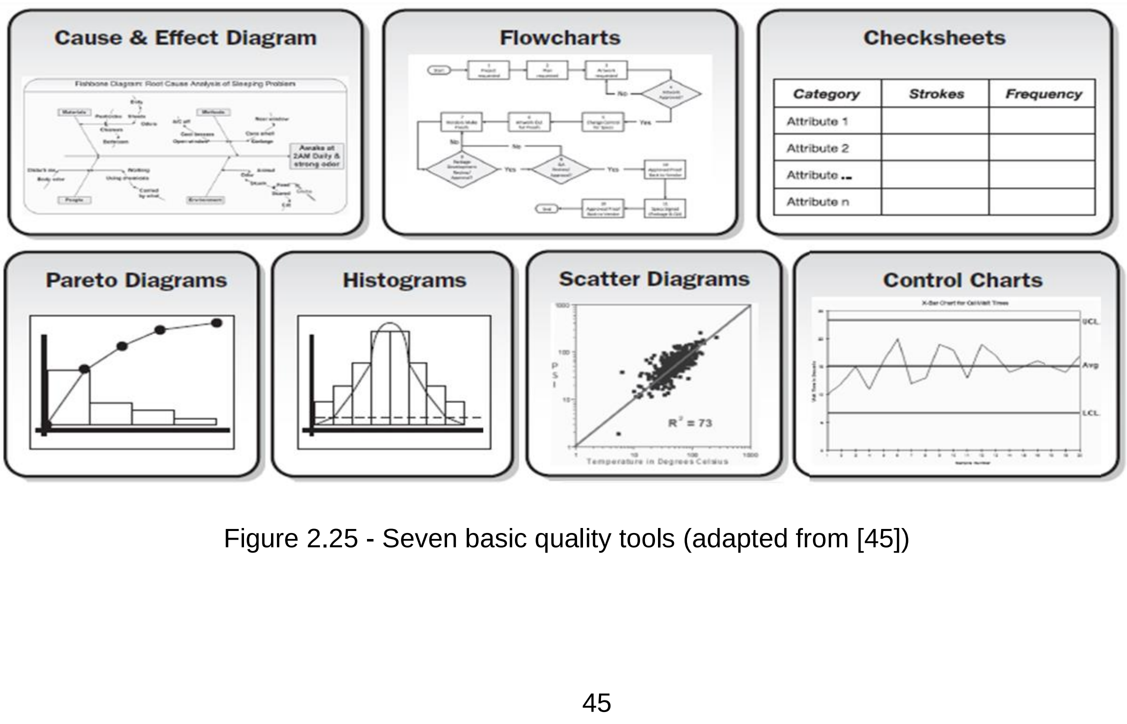


Figure 2.25 - Seven basic quality tools (adapted from [45])

Besides all these presented tools Six Sigma has adopted many more over the years depending on applications. Amongst them there are two that are of interest to aid design decision-making and concrete problem-solving. The first is Axiomatic Design and the second is the Theory of Inventive Problem-solving (TRIZ). The next topics present both these tools.

2.5.6. Axiomatic Design

Axiomatic Design (AD) is a general methodology to structure and understand design problems so as to help in the synthesis and analysis of suitable design requirements, solutions and processes. AD provides a consistent framework from which metrics of design alternatives can be quantified. It derives its name from the word axiom meaning a statement taken to be true (as in given without proof) to serve as a premise for further reasoning. Its main reasoning is that the physical components should be aligned to the functional requirements [46].

AD theory is based on two axioms. The first Axiom, the Independence Axiom, maintains the independence of necessary Functional Requirements (FR). For a design to be acceptable Design Parameters (DP) can be adjusted to fulfil its corresponding FR without affecting other FRs. The second Axiom, the Information Axiom, minimizes the information content of the design so that the best design is the design with the minimum information content. In short, the first axiom allows for the exploration of several designs and then the second axiom chooses the best one based on their information content [46]. Analytically these relationships are explored by:

$$[FR]_m = [A]_{m\times n}[DP]_n \tag{2.1}$$

$$[DP]_n = [B]_{n\times l}[PV]_l \tag{2.2}$$

In practice, the AD methodology presented in Figure 2.26 starts by having the customer expressing its customer needs (CN) and expectations. These are then used to define functional requirements (FR) that describe the necessary functions i.e. what the product, service or process should exactly do to fulfil an intended CN. Afterwards FRs are characterized into the various technical features of the components needed to execute those functions by virtue of defining design parameters (DP). Finally a correspondence to actual process variables (PV) brings forth the necessary process variables to act upon to produce the desired results. Throughout all this process constraints and project requirements are always present and impose limitations to all possible solutions. To deal with this and decompose general requirements a back and forth approach between all of these is suggested to find solutions.

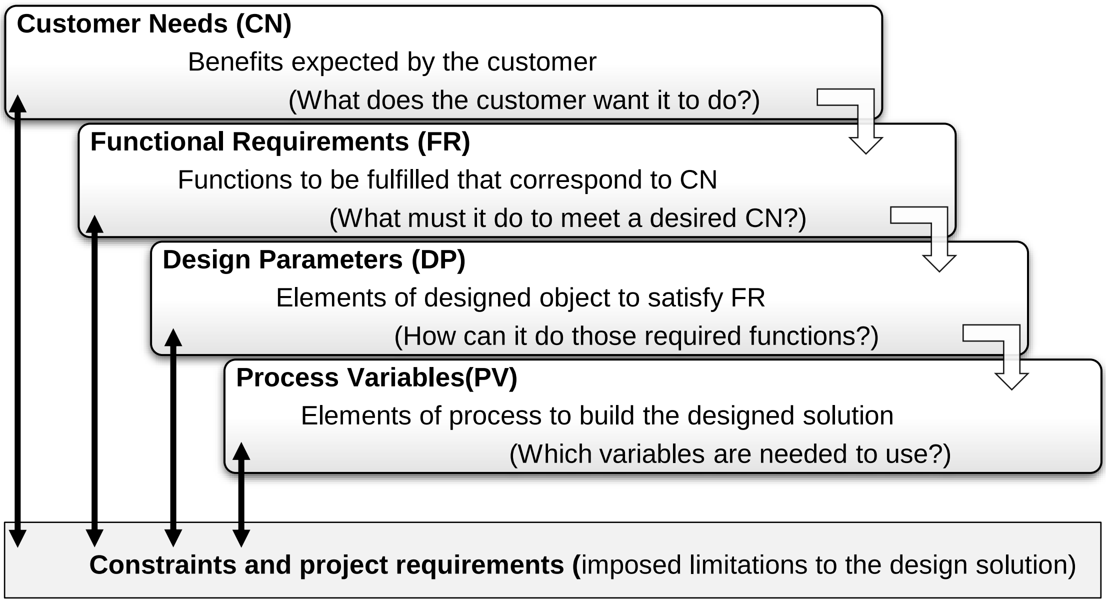


Figure 2.26 - Axiomatic Design methodology (adapted from [46])

2.5.6.1. Customer needs and the Kano model

The first step in AD and the cornerstone for its success is to identify what the customer wants and the benefits expected. For this effect following the Kano model principles will help define CN's and their importance. The Kano Model (Figure 2.27) is a theory for product development and customer satisfaction and represents the perception of importance of needs to the customer [47].

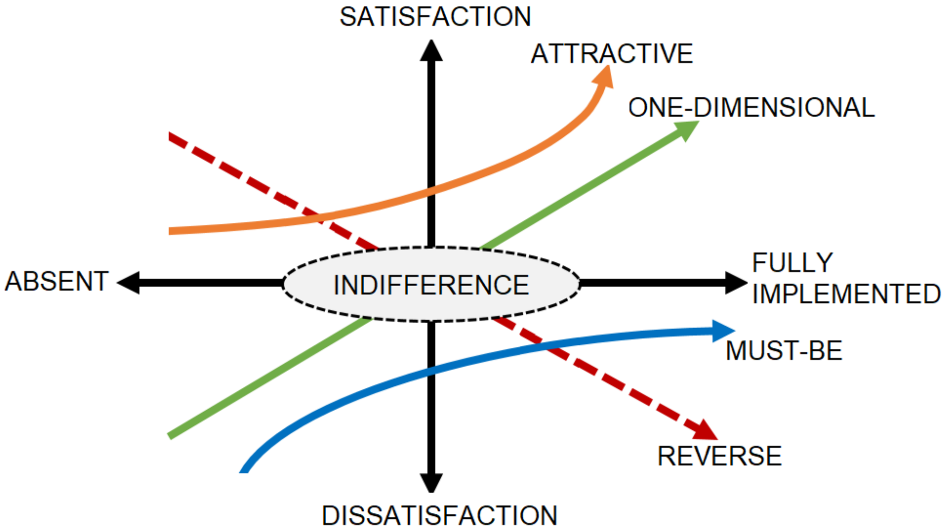


Figure 2.27 - Kano model (adapted from [47])

Kano model's graphical representation is a rough sketch on achieving customer satisfaction by means of a qualitative assessment of a product's quality attributes. These are divided into the categories of Must-be, One-dimensional, Attractive, Indifference and Reverse and each one represents a level of impact of single attributes on customer satisfaction [47].

- Must-be attributes are the basis of a product/service and can be considered as the bare minimum as the customer implicitly takes them for granted. Their absence is a cause of great dissatisfaction as they can be looked at as prerequisites that don't contribute to increasing customer satisfaction even when met. These are often unspoken.
- One-dimensional attributes are explicitly expected by the customer leading to a linear relation between customer satisfaction and fulfilment of these expectations. The more these are fulfilled the higher the customer's satisfaction will be and vice versa.
- Attractive attributes are the ones explicitly demanded by the costumer. Since these aren't expected fulfilling these leads to more satisfaction but when absent also don't imply dissatisfaction.
- Indifference attributes are the ones that have no influence in customer satisfaction.
- Reverse attributes are the opposite of One-dimensional ones as their presence actually causes dissatisfaction.

2.5.7. Theory of Inventive Problem-solving

The theory of inventive problem-solving (TRIZ) is a Russian problem-solving methodology that offers a wide range of concrete tools to aid in process design and problem-solving. TRIZ tools were created and evolved from researching worldwide patents for technological solutions. TRIZ tools form a knowledge base which includes 40 Inventive Principles, 76 Standard Solutions and an Effect Database, [48]. TRIZ problem-solving algorithm is presented in Figure 2.28.

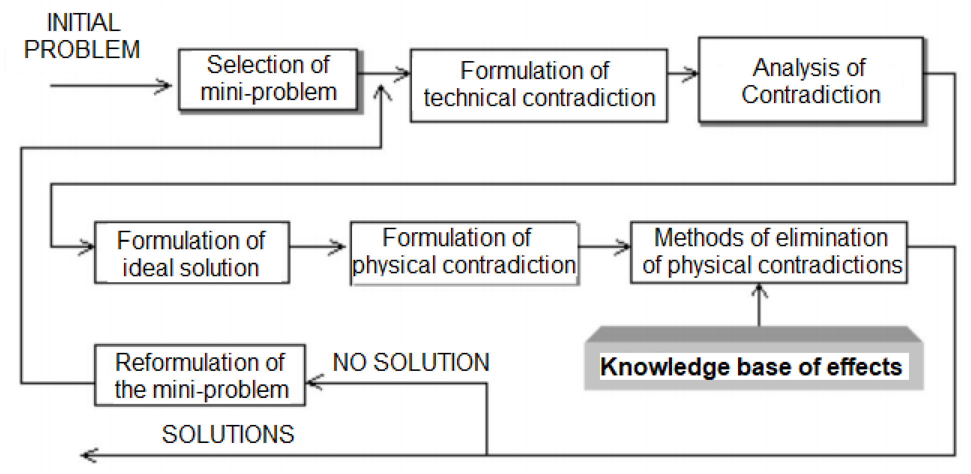


Figure 2.28 - Inventive problem-solving algorithm (adapted from [48])

TRIZ is supported by a contradiction matrix for developing inventive solutions. Each solution is a recommendation for a possible specific change in order to eliminate technical contradictions. This contradiction matrix is widely disseminated in literature and can also be found in the form of an online interactive tool (e.g. triz40.com). A classic example is of the need to make a static object longer without becoming heavier. TRIZ principles suggest, amongst other possibilities, to try and change the object's physical state (solid/liquid/gas), its consistency, its flexibility or its temperature in order to find a new design. [48][49].

Throughout this work several tools have been looked at that prove to be useful inside a methodology. To finish this supporting chapter, strategies and methodology models will be looked at providing the basis for a proposed methodology format in which these tools can be present.

2.5.8. Migration strategies

Differing in the general techniques used, three different migration strategies to transform a legacy system into a target system can be found in literature. These are the Big Bang, the Parallel Systems and the Phased Introduction. Although these strategies mainly concern migration of Information Systems, they still offer valuable knowledge in terms of general characteristics, advantages and disadvantages, [50]. This information is summarized in Figure 2.29:

	Big Bang	Parallel	Phased
Risk	High	Low	Medium
Migration Design Time	High	Low	Medium
Migration Execution Time	Low	Medium	High
Down Time	High	Low	Medium
Cost (Effort)	Low	High	Medium

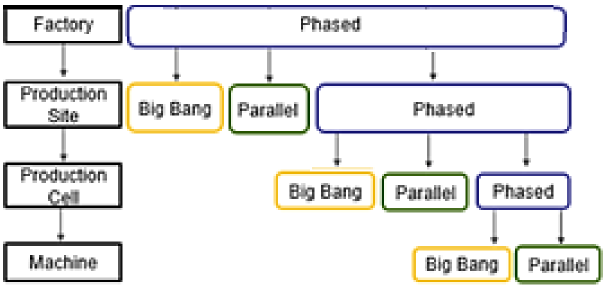


Figure 2.29 - Migration strategies comparison (left) and recursivity (right) (adapted from [50])

- Big Bang: Described as a change in a single moment in time, with this the legacy system is switched off and the target system is immediately switched on. Its advantages lie in the little amount of time spent for implementation, lower costs because of no need for intermediate systems or duplicated resources and workers training not wasting time in learning to deal with transition situations. The big drawback is the fact that it is a huge risk strategy because of the difficulty of recreating all the conditions of an actual production environment. This means that any failure, as small as it may be, can quickly escalate becoming very difficult to resolve or even fatal. In addition, workers training must be done in very little time. This strategy is suitable for migrating production systems in need of complete technological and/or organizational changes [50].

- Parallel Systems: Here both legacy and target systems run in parallel, i.e. they run at the same time for a certain period of time necessary to execute, test and validate the correct operation of the target system. Only after that the legacy system can be switched off, or eventually be left running for temporary redundancy insurance albeit with additional costs to the migration process. This is an advantage in case of failure because it is possible to roll back to the legacy system in such case. With both systems running together synchronization between them is required as all transitions will be carried out in both systems which adds costs to the migration process. Additionally, the duplication of systems implies high implementation costs and necessity of a bigger number of resources. However, having both systems running means low probability of errors hence this being a low risk strategy. In addition, real-time comparisons between both are possible allowing for improvements to be carried out during the transition. This strategy is adequate for migrating small production lines that cannot survive with a major system failure [50].
- Phased Introduction: This strategy stands for a gradual carefully planned transition. It requires studying interdependencies and processes to determine the correct sequence of the migration phases. The implementation is done block by block according to planned sequence and timing, shutting down the replaced legacy system's blocks as implementation progresses. This allows for feedback between phases promoting continuous system improvements. Due to its low level complexity it stands for lesser risk and lesser resources required. It does carry the burdens of medium implementation costs (relative to others) and high implementation time but that time can be used to better train and adapt workers to changes. Depending on application the blocks of the Phased Introduction strategy can be just machines, cells or entire production cells, where in the smaller blocks other strategies can be used independently [50].

2.5.9. Plan-Do-Check-Act cycle

The Plan-Do-Check-Act (PDCA) cycle is a four-step model used as a project planning tool for carrying out changes to improve the quality of a process. It is represented by the circular shape presented in Figure 2.30 to symbolize that it is non-ending, i.e. the cycle should be repeatedly executed for continuous improvement. The PDCA four phases activities are [51]:

- Plan: Recognizing an improvement opportunity and planning a change
- Do: Performing a small-scale study to test a change and obtain results
- Check: Reviewing the test and analysing its results
- Act: Based on the results decide on improvements, either by improving the successful change or repeating the cycle with another solution if the previous was unsuccessful.

Figure 2.30 - PDCA cycle (extracted from [51])

Amongst many applications, the PDCA cycle can be used for developing new designs for product, process or service improvements, planning for best ways for data collection and analysis, implementing changes to processes and to promote continuous improvement [51].

The PDCA cycle is also the basis for various problem-solving methodologies such as DMAIC, A3 Report or 8D problem-solving. As seen before, DMAIC with its 5 steps is the basis of Six Sigma and has a strong emphasis in statistical analysis. The A3-Report, developed by Toyota, is an 8-step PDCA that fits on an A3 sheet of paper and is mainly a visual tool. The 8D problem-solving process widely present in automotive industries evolved over time to a 9-step PDCA and focus on reacting quickly to customer complaints. Table 2.4 maps each other's phases [52]–[55].

Table 2.4 – Phase comparison of PDCA, DMAIC, A3 and 8D (adapted from [52]–[55])

<table>
<tr><th>PDCA</th><th>DMAIC</th><th>A3 Report</th><th>8D problem-solving</th></tr>
<tr><td rowspan="5">Plan</td><td>Define</td><td>Clarify and validate the problem</td><td rowspan="2">D0: Identify problem and plan actions
D1: Form team
D2: Describe problem</td></tr>
<tr><td rowspan="2">Measure</td><td>Break down the problem</td></tr>
<tr><td>Set an improvement target</td><td>D3: Contain the problem</td></tr>
<tr><td rowspan="2">Analyse</td><td>Determine root causes</td><td>D4: Identify and analyse root causes:</td></tr>
<tr><td>Develop countermeasures</td><td>D5: Define corrective action</td></tr>
<tr><td>Do</td><td>Improve</td><td>See countermeasures through</td><td>D6: Implement corrective actions</td></tr>
<tr><td>Check</td><td rowspan="2">Control</td><td>Evaluate results and process</td><td>D7: Prevent recurrence</td></tr>
<tr><td>Act</td><td>Standardize successful processes</td><td>D8: Congratulate team</td></tr>
</table>

2.5.10. German VDI/VDE Guideline 3695

The German VDI/VDE Guideline 3695: “Engineering of Industrial Plants – Evaluation and Optimization” establishes its own model for continuous improvement (Figure 2.31), [56].

It defines a recurrent cycle of sequential phases that start by measuring and analysing the current state. In the next phase a target state is defined so that in the third phase it becomes possible to compare both. Afterwards appropriate measures can be defined and planned in order to be able to reach the desired target state. Then these measures are implemented and in the final phase its results are reviewed. The cycle is then restarted.

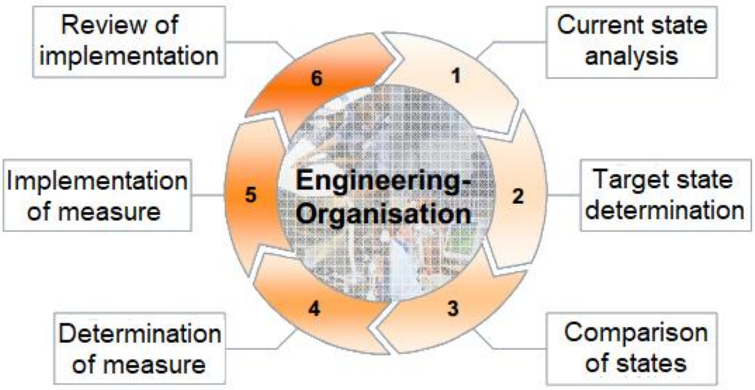


Figure 2.31 - VDI/VDE Directive 3695 (adapted from [56])

DMAIC, PDCA and the VDI3695 stand out in current literature as basis for many authors to propose their own methodologies for either designing from scratch and/or implementing changes to systems, processes and products [50][57][58]. From this analysis it is retrieved the concept of continued cycle iteration for promotion of continuous improvement. Others concepts of value are the deconstruction of phases into smaller tasks for promoting simplicity of application and the necessity to analyse a system’s current state to determine future improvement possibilities

In conclusion, I4.0 as a new paradigm stands for the redefinition of organization and control methods of value-adding activities. Its scope covers all areas such as order management, research and development, production, commissioning, delivery to use or recycling of produced goods. Thus, for this to be realised it introduces the concept of full integration of functional areas and assets, i.e. workers, systems, products and resources, as well as the concept of smart, self-organized, cross-corporate, real-time and autonomously optimized instances.

Technologically the widely accepted path to I4.0 is through the dissemination of CPS. To fully realise CPPS, first integration of physical and cyber processes has to set up on individual systems to effectively create individual CPS. By interconnecting all CPS and building a decentralized automation system it is then possible to bring together smart machines, storage systems and production facilities, able to autonomously exchange information, trigger actions and control each other independently.

This advancement in technology also implies that human roles must be redefined, going forward as CPPS substitute humans in the standard and routine decision situations. In I4.0 humans workers have to be retrained and gain new competences in order to be reintegrated as the fundamental basis for CPPS success since they will be the ones in charge of the vital tasks of understanding, interpreting, evaluating, verifying and using CPPS generated information.

On the organizational side, as the transition to I4.0 is worldwide ongoing and gaining heavy momentum it is up to top management to be proactive and start developing strategic migration paths. This means changing traditional ways of being and allow for more experimentation, risk-taking and collaboration in order to remain competitive in an ever-increasing aggressive market.

Furthermore, several Lean Management concepts, tools and techniques were looked at and how new technologies can benefit them. These allow to promote waste reduction, continuous improvement, better productivity, better production flexibility and reduction in complexity of tasks. Additionally, some design techniques and methodologies were reviewed as they were deemed important and relevant given the scope of this work that intends to target all stages from design to deployment of new systems.

All of these together will now be the support for the development and proposal of a methodology to support Cyber-Physical Production Systems Design, Development and Deployment (CPPS-3D).

Chapter 3.

CPPS-3D: A methodology to support cyber physical production systems design, development and deployment

This chapter presents the proposed methodology describing its various stages. CPPS-3D consists of two main phases. The Assessment phase characterizes an enterprise across three dimensions, namely Technological, Organizational and Human and identifies possible gaps towards I4.0. The Project Development phase is a guide for enterprises to design and deploy a concrete solution to fill an identified gap.

3.1. CPPS-3D Overview

I4.0 is an ongoing (re)evolution with promises to achieve sustainable unprecedented levels of productivity, flexibility and efficiency. However a higher number of more complex products, new production processes, growing competition through internationalization, and especially new technologies in markets with rapidly changing conditions are a tremendous challenge for enterprises. To maintain their competitiveness in these dynamic and turbulent environments, it is imperative that enterprises become able to anticipate and address these changes as the I4.0 digital transformation will be a key factor for economic success.

I4.0 brings forth the promises of many benefits through its intended technological integration of all systems across the enterprise. However, the technological advancement must be made in conjunction with simultaneous evolutions in both the organizational and the human dimensions. They are all intertwined and the transition all three.

As seen before, the implicit advantages and benefits of I4.0 seem to be clear but the way to get there is still yet not clearly defined. At present research is still ongoing and many authors offer their own different contributions and views meaning there is a clear need to help enterprises and their employees going forward. What was shown was that the general agreement in literature is that CPPS are the technological key to unlock full I4.0 potential. A CPPS is built upon the implementation and digital interconnection of several CPS. Starting at the shop floor, CPS are created by providing sensing and communications to machines, parts and workers. Once this basis foundation is established, the CPPS is then built up through all enterprise levels in increasing physical-abstraction layers up to the cyber space.

The most fundamental characteristics of CPPS are its use of innovative technologies and digitalization of productive processes by means of CPS implementation. Nonetheless this still currently involves many fields of research and several challenges to be addressed. Adopting this new paradigm requires carefully planned investments as enterprises don’t have the resources to completely renew all their processes at once. This is a good example where the previously presented concept of Phased Introduction (see 2.5.8-Migration strategies) is adequate as it allows for the testing and implementation of new smaller systems. This way the migration can be very doable allowing for sustainable optimization of processes as small projects will be more manageable with less resources allocated.

Motivated by the perceived needs to help and to guide enterprises in evolving into I4.0, to accelerate product introduction or process changes and to ensure profitable life cycles of innovation and process improvement in this new era of production, it is proposed a methodology for Cyber-Physical Production Systems Design, Development and Deployment (CPPS-3D). Through its phases CPPS-3D takes into consideration the Organizational, Technological and Human dimensions of I4.0. Furthermore it explores their relationships as all three are closely intertwined and naturally overlap themselves so in addition overlapping regions are defined as presented in Figure 3.1.

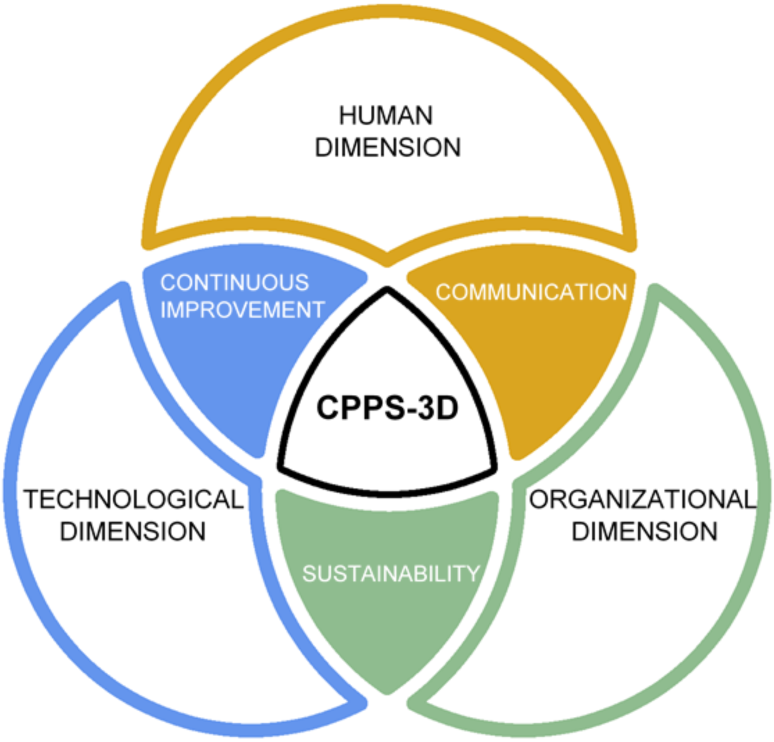


Figure 3.1 - CPPS-3D dimensions and relationships

- Communication

In Chapter II, when the Organizational dimension was discussed, several management challenges brought forth by I4.0 (see the framework in Figure 2.18) were identified. In it some important management challenges identified were the need to create acceptance for change as well as the establishment of a culture of collaboration, issues closely related to the topics of improving the workplace and qualifying the employees. This clearly defines the necessity for Communication, hence the choice of this term for defining the intersection of Human and Organizational dimensions. Communication between workers and management is fundamental for a successful enterprise. Bottom workers are a valuable asset as they gain expert process knowledge by practice. This in turn can offer valuable insights to management for planning a more flexible and productive workplace. For this to happen social competencies are a must to be worked on by means of continuously promoting actions across the enterprise to develop them. These include values such as ability to work in a team, capability to transfer knowledge, leadership skills, conflict-solving aptitudes and appropriate ways of interpersonal communication [59]. Social competencies are fundamental as a foundation for promotion of interactions between individuals and greatly influence how these same individual develop perceptions of their own and of others behaviours. These premises must be present in the management focus required for the changes promoted by I4.0 projects.

- Sustainability

Relating back again to Chapter II and the previously mentioned framework of management challenges (see the framework in Figure 2.18), a close relationship was also established between management challenges and planning technological migration paths in order to evolve into I4.0 in a strategic supported way. From the implications that adequate planning and strategy are fundamental challenges for promoting I4.0 future, the category of Sustainability was derived for defining an intersection of the Organizational and Technological dimensions. With Sustainability as a support, introduced technological changes must be evaluated and controlled to ensure that they continue to add productivity, quality and safety benefits long after their implementation. Sustainability also greatly depends on developing management competencies. These include cultivating skills and abilities for general problem-solving and decision-making such as creativity, entrepreneurial thinking and efficiency orientation, as well as developing research and analytical skills [59]. Management competencies should focus on building up expertise to make better supported business decisions and lead subordinates into acceptance of changes.

Moreover Sustainability also relates directly into the needs of monitoring and evaluating improvement projects. Collecting information for monitoring processes should happen routinely. This way discrepancies between planning and implementation are quickly recognized and adjustments can be made. Then evaluation of the effectiveness of the changes introduced can provide valuable information to decision-makers to help them determine performance and productivity gains. This will also serve as a learning tool for selecting and handling future projects as well as on how to improve methods and outcomes. Being able to recognize what improvements were achieved demonstrates accountability, acts as global motivator for renewing efforts and brings in a sense of accomplishment. This in turn will promote the mentality required to engage in another following improvement project where little by little the enterprise has sustainable growth. Nevertheless, evaluation should never be intimidating but instead be perceived as constructive criticism that reveals new areas of improvement.

Finally the necessity of standardized work and the importance of knowledge development and transfer also lead into the concepts of Sustainability and imply documenting current practices to form standard operating manuals. These documents then serve as global knowledge basis for the enterprise and potentiate continuous improvement. This way the enterprise not only guarantees specific knowledge is always accessible and not dependent on a few people, but also benefits from reducing process variation, increasing productivity, reducing costs and improving quality of both processes and products.

- Continuous improvement

As for the relation between the Technological and Human dimensions, it was formerly presented the complementary 5C architecture for Cyber Human Systems (see Figure 2.17). In it, as CPPS become more advanced, human roles need to evolve up to supervisory and exception-handling roles. This is coherent with promoting a philosophy of continuous improvement and in that sense Continuous Improvement was chosen as a reference for the intersection of these dimensions. In addition it is also a further reinforcement of the needed mentality to progress into I4.0 by taking advantage of humans' knowledge and creativity. Only this way will be possible to explore new and innovative ways to improve processes and adapt technology to assist human workers and develop their skills.

Evolving the human roles will also lead into the inevitability that by removing routine tasks from humans, developing a critical sense to tasks being performed and environments will become an imperative need. Subsequently this will feed the Continuous Improvement mentality by enabling constant rational feedback by workers involved with new technologies introduced. Their critical minds and everyday practice learning can provide the insights to problem-solving and to better analyse technological alternatives and determine the optimal methods and frequency for results analysis. Finally the Technological and Human dimensions are also closely related in the sense that Continuous Improvement can consist of deploying small improvement projects one at a time. From this, practice and expertise in project definition and management can be gained as added value while expanding technical competencies of all involved. These competencies are the necessary job-related knowledges such as for example coding skills, marketing techniques or specific software proficiency [59]. These competencies are the kind that only through learning, applying and everyday practice will benefit and enhance an individual's performance at their particular role.

With that said, CPPS-3D methodology is proposed in Figure 3.2.

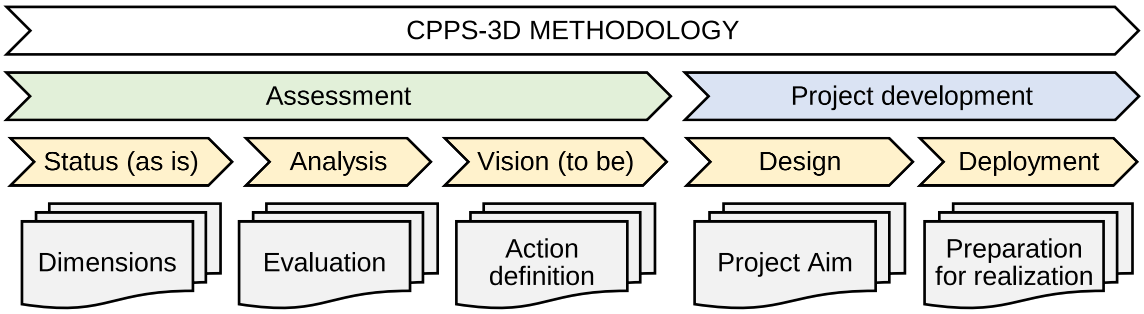


Figure 3.2 - CPPS-3D methodology

As a whole CPPS-3D consists of two main development phases namely Assessment and Project Development. These represent two distinct work phases with different objectives. By virtue of this each phase can be carried out by different teams which translates into better human resources management.

The decomposition of the Assessment and Project Development phases of CPPS-3D into finer details produces the vertical subordinate elements detailed in Figure 3.3. Each phase is built upon sequential steps so Assessment contains the Status, the Analysis and the Vision steps while Project development includes the Design and the Deployment steps. Each step then indicates Focus Points (FP) that target specific topics which act as guidelines for directing efforts. Finally each Focus Point has a series of topics named Elements of Interest (ELI) that act as enablers for discussion, reflection/reasoning, decision-making and action-taking needed to address the relevant issues to further progress in the methodology.

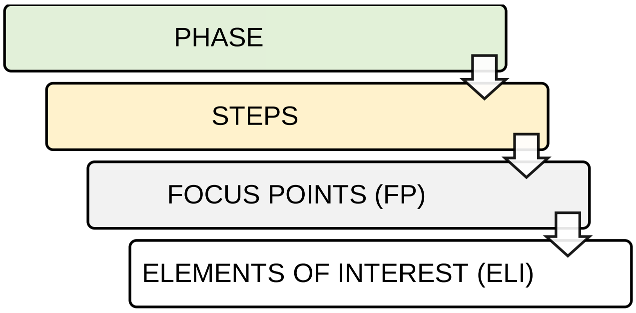


Figure 3.3 - CPPS-3D vertical detail concepts

The sequence of phases to conduct the methodology is inspired by circular models that promote continuous improvement, such as PDCA and VDI/VDE 3695, which promote a sequence of phases each with its own particular purpose. Presented resources of product design and development methodologies such as Axiomatic Design influenced the definition of steps pertaining to each phase. Along its path CPPS-3D takes into account the three dimensions of I4.0 to look for the Focus Points of each step. Finally resorting to LM philosophy enables the identification of tools and methods to be used in the different ELI.

As mentioned, CPPS-3D has two main distinct phases: the Assessment and the Project development. First in the Assessment phase the focus of the methodology is to rate several key processes in order to determine the current status and set goals. By this it is possible to evaluate the level of development and the conditions for the enterprise to carry out I4.0. This assessment considers different areas and categories, aligned with LM philosophy and principles, therefore being very much focused in processes of the existing value chain. The assessment, due to the general concepts behind it, evaluates the level of preparation for I4.0 being applicable to industrial and service enterprises.

After the Assessment phase a particular goal or goals should be selected and those goals should be used to drive the second phase of the methodology, the Project development. This phase is carried out in order to achieve chosen goals. It requires strategic thinking, customer input, technical discipline, expertise knowledge, creativity, speed and innovation to ensure a successful output. For this the methodology behind Axiomatic Design (AD) is proposed as guidance.

Promoting a philosophy of continuous improvement, afterwards the cycle is restarted with the evaluation of results and decision on next project. The next sub-chapters of this work go into the fine details of each phase of CPPS-3D.

3.2. CPPS-3D Assessment phase

To determine where to start first there's a necessity to know where and how the enterprise stands. For this CPPS-3D starts by conducting the Assessment Phase represented in Figure 3.4. This phase targets several key issues in the enterprise as to determine its current status and upon analysis its future goals. As described before, each step will have different Focus Points (FP) that will be further expanded into defining Elements of Interest (ELI) required to be acted upon.

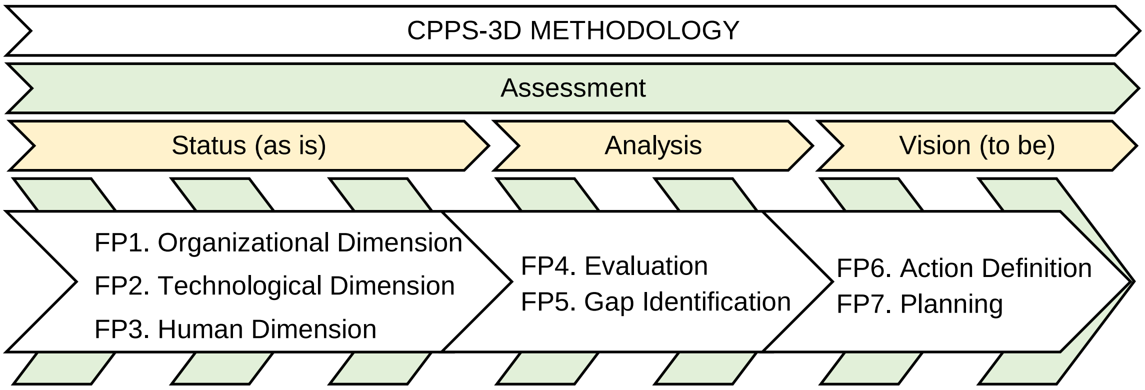


Figure 3.4 - CPPS-3D assessment steps

3.2.1. Status step

The Assessment begins by looking at the current situation of the enterprise. It is proposed to look at all dimensions implied within the I4.0 paradigm, Organizational, Technological and Human. These form the first three FP and for each one were defined corresponding ELI for guidance (Table 3.1).

Table 3.1 - CPPS-3D Status Step

PHASE: ASSESSMENT		
STEP: Status	FP1: Organizational dimension	ELI1. Product ELI2. Processes ELI3. Value chain
	FP2: Technological dimension	ELI1. Production equipment ELI2. Support systems ELI3. Integration level
	FP3: Human dimension	ELI1. Function and levels ELI2. Competencies ELI3. Leadership

3.2.1.1. FP1. Organizational dimension

Looking at the organizational dimension allows for a better perception of the enterprises competitiveness and sustainability. In accordance the following three ELIs are proposed:

- ELI1.Product: First and foremost the one indispensable element is obviously the product as without it there would be no enterprise. An understanding of how the product responds to customer needs is essential. This will affect production and its supporting functions since better operation efficiency and lower costs can be targeted by redefining product attributes. Internally in the enterprise customer satisfaction can be prioritized by promoting a culture of employee awareness towards production and services quality. Being costumer focused leads into the overall success of the enterprise and this can be accomplished by resorting to market research and quality analysis tools. For that useful tools are the Kano model, QFD and FMEA.
- ELI2.Processes: This intends to perceive how production processes are organized, integrated and monitored. Integration and efficiency are key here as energy and materials consumption reduction leads to lower costs and better yields. Planning for flexibility of machines and decreasing downtimes as well as changeover times by means of effective methods of predictive maintenance are also key factors to consider. Besides that, productivity can also be increased by reducing waiting times and workers tasks complexity. At this stage of CPPS-3D useful tools are the 7 basic quality tools, particularly Histograms, Control charts and Pareto diagrams. These methods and techniques are used for the gathering and analysis of information.
- ELI3.Value chain: In order to deliver a valuable product to the customer a number of activities have to be performed. Starting from its input, through its transformation processes and ending in its outputs the complete production process will involve the consumption of resources e.g. materials, equipment, labour. The way this is all managed greatly determines costs and revenues. Attempting to decrease non value adding activities must always be something in mind and this can be achieved by means of establishing audit and control processes to identify problems. In accordance a useful tool is VSM as it allows to better understand the flow of operations of the enterprise. Striving for quality and safety are also important aspects that should not be overlooked so implementing continuous statistical control mechanisms like the 7 basic quality tools will result in better products and customer satisfaction. In addition promoting safe workplaces and products can avoid many costly problems. These aspects of the value chain are beneficial to the enterprise so their assessment is justified.

3.2.1.2. FP2. Technological dimension

The fulfilment of CPPS promises is deeply intertwined to I4.0 technology advancements. This is true not only at the physical layer of production i.e. machines, tools, sensors, communications, but also at the higher up levels where the complexity of software leads into the further abstract levels of cyberspace. In this sense when looking at this dimension an assessment must contemplate the actual physical production equipment and then all its support systems coupled with how well do these all integrate together. Another important and deeply related aspect to this dimension is continuous improvement by which problem-solving solutions and performance improvements can be obtained. The defined ELIs are as follows.

- ELI1.Production equipment: As CPPS will inevitably evolve from the traditional 5C architecture where it stands now into more decentralized networks it is important to remember that in a CPPS all production assets are to be interconnected. For this to happen sensing and communication capabilities are a must for all production elements. This is the most basic foundation stage of I4.0 as collecting accurate and reliable data is vital. Evaluating these capabilities allows to understand where an enterprise currently is and where it is possible to go next technologically speaking. More advanced production equipment promotes reduction of workers tasks complexity and more efficient standard work routines thus contributing to avoidance of production errors. Besides that reliability and robustness of equipment are also very important in an industrial environment for achieving more cost efficient processes. As one looks at the production equipment it is also inevitable to take into account what their function is and how it contributes to respond to the actual product's requirements. For this, at this stage of CPPS-3D, a useful tool to consider is QFD.
- ELI2.Support systems: The purpose of evaluating these elements is to get an idea of the existence and technological level of existent production support systems. These include management software such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES) or Supply Chain Management (SCM). Support systems also include establishing the means to deal with problems, finding solutions that not only fix the immediate but also improve performances by doing so. This implies the existence of a management system that actively promotes collaboration and sharing of improvement ideas by all.
- ELI3.Integration level: With this it is intended to better understand the levels of systems integration across the whole enterprise. CPPS are deeply related to the concept of both-ways data and information sharing so this relates to establishing a collaborative scenario of real time sharing between all involved in production from workers to management, as well as possibly outside to suppliers and customers. Establishing integrated systems both at horizontal and vertical levels means finding ways to deal with different levels of automation and information flow.

3.2.1.3. FP3. Human dimension

With I4.0 the human roles will have to be reconsidered and shifted from the routine tasks to more evolved thinking-needed roles. Human workers functions will be very different with the full establishment of CPPS so requalification and continuous learning of new competencies is a key factor in going forward. In addition leadership roles must also evolve to keep up with the I4.0 (re)evolution. In this sense the following ELIs were defined.

- ELI1.Function and levels: First employee functions must be looked at. As CPPS continues to evolve routine tasks and decisions are transferred from humans to machines. As this happens worker's functions, roles and level of responsibilities also shift. Ultimately in the future humans are to be left with supervision roles and the handling of exceptions where it won't be feasible to have a CPS running. And for that retraining and requalification of human workers into new competencies and skills at all levels is critical, with the benefits of also providing human resources versatility.
- ELI2.Competencies: The needs for new competences have to be identified and acquired so having established channels to make this happen is mandatory. Requalification of workers into new tasks requiring new skills allows for greater flexibility of operations. Additionally technological areas such as automation, robotics, industrial communications, data analysis, management systems and systems integration are examples of new fields of work where advanced competencies are a must. Management itself also faces an impending need to further develop competencies that allow for better adaption to increasingly demanding markets, e.g. creative problem-solving, research and analytical thinking or conflict management.
- ELI3.Leadership: What is intended here is to evaluate leadership involvement across the enterprise. The roles of leadership need to evolve to new values to ensure that the transition to CPPS is successful. The technological advancements will make human values and ethics delicate issues in need of careful considerations, particularly when dealing with evaluation of workers performance. Leaders will benefit from instilling a sense of purpose to subordinates and promote healthy and collaborative work environments. Creating these appropriate conditions will then facilitate to establish proper communication channels for operations management.

3.2.2. Analysis step

After the identification of key elements in the previous step, it is proposed an analysis of the current status of the enterprise. This analysis is intended to provide insight into the existent enterprise situation and promote the identification of gaps towards the development of CPPS. These form the FP for this step that are then deconstructed into corresponding ELI for guidance as per Table 3.2.

Table 3.2 - CPPS-3D Analysis Step

PHASE: ASSESSMENT		
STEP: Analysis	FP4: Evaluation	ELI1. Measurement ELI2. Dimension profile ELI3. Business model
	FP5: Gap identification	ELI1. Qualification and training ELI2. Equipment and processes ELI3. Organization methods

3.2.2.1. FP4. Evaluation

Following the description of key elements in the previous step a qualitative analysis of the enterprise ensues. It is meant to complement the previous step's observations by defining a way to measure its current situation. This will provide support for further reflection and discussion on current status and allow to subsequently proceed into identifying gaps.

- ELI1.Measurement: In order to later identify gaps here a concrete measure of different aspects of the enterprise has to be defined. This intends to provide a qualitative analysis on current enterprise status across all mentioned dimensions. Furthermore it is proposed that the 5C architecture levels be adapted and used as reference to that measure. This allows to compare the actual enterprise state with the possible ways to evolve towards CPPS. For that it was developed an assessment guide (see 3.2.4) in which categories across all dimensions were defined. This, together with the report of observations of the previous step, will provide a more complete representation of all areas across the enterprise.
- ELI2.Dimension profile: This evaluation is meant to try and understand how the enterprise faces itself in the market and where its dimension and attitude can lead them to. According to organizational culture profiles [60] an enterprise is characterized mainly by one of these different possible organizational cultures:
  - Innovative and risk-taking when it's adaptable and encourages experimenting with new ideas
  - Aggressive when valuing competitiveness and beating its competitors
  - Outcome-oriented when achieving proposed results are rewarded
  - Stable when the organization is predictable with strict established rules
  - People-oriented when it considers people their greatest asset and promotes support and respect for individual rights
  - Team-oriented when collaboration and cooperation between all levels of employees is key
  - Detail-oriented when all focus is on getting details absolutely right and exceeding costumer expectations.

- ELI3.Business model: An analysis of the current business model should be conducted when introducing major changes or if deemed necessary. Business models establish the connections between product/service and customers by means of establishing the enterprise's value proposition and defining their targeted customer segments. To conduct a proper assessment of the business model it is possible to resort to the visual tool Business Model Canvas, a one-page canvas divided into nine building blocks.

3.2.2.2. FP5. Gap identification

Having identified and evaluated the current status of the enterprise the next logical path is to determine the gaps towards the evolution of the enterprise as a whole. In this sense next are proposed the following ELI based each one on a different dimension:

- ELI1.Qualification and training: Evolving into CPPS requires that the human factor be re-evaluated in regards to its contribution. While automation and computation takes over the more routine and predictable tasks, employees must gain new qualifications and be retrained into new roles as previously discussed. At this point and depending on introduced changes the needs for employee’s new qualifications and new tasks training have to be determined in order to be able to correctly identify any significant gaps.
- ELI2.Equipment and processes: The concept of CPPS implies flexibility and adaptability by means of new technologies which directly relates to necessities of evolving machines and processes. So possible new technologies should be studied and their benefits assessed in order to determine the technological gaps and possible benefits.
- ELI3.Organization methods: This determines if the enterprise is underperforming in relation to its identified organizational dimension elements. In the evolution into I4.0 it is implied as a major driver that communication and information sharing are fundamental. In this sense the ways that the enterprise functions should be scrutinized so that organizational gaps are revealed.

3.2.3. Vision step

After the current status evaluation is completed and gaps identified the final step in the assessment phase is to establish a future vision for the enterprise in terms of pursuing CPPS goals and the necessary actions to realize it. The FPs and corresponding ELIs presented in Table 3.3 are proposed for this purpose. Additionally a developed assessment guide table (see 3.2.4) allows to visually create a common ground for discussion about opportunities for further developments.

Table 3.3 - CPPS-3D Vision Step

PHASE: ASSESSMENT		
STEP: Vision	FP6: Action definition	ELI1. Product-service ELI2. Processes ELI3. Resources
	FP7: Planning	ELI1. Requirements ELI2. Competencies ELI3. Priorities and risks

3.2.3.1. FP6. Action definition

After the previous gap identification is carried out ponderation and discussion on next attainable goals should be promoted. This will allow to define what type of changes will be needed to be able to close identified gaps.

- ELI1.Product-service: Generally speaking the customer doesn't know what product they want, only the result they expect from it. Improving the product/service to meet their expectations implies that a series of actions have to be carried out to redefine the product. At this stage of CPPS-3D resorting to Axiomatic Design workflow allows for a comprehensive understanding of customer need and its implications towards satisfying them.
- ELI2.Processes: Establishing beforehand the necessary actions to (re)define the product, the necessary modifications to production and organizational processes must be considered. At this point necessary changes to these processes need to be identified in order to define what needs to be done to execute them.
- ELI3.Resources: With the changes in product and processes, additional needed resources such as materials, technology and workers must also be defined. From this a complete global vision on what necessary actions are mandatory across all areas to achieve each proposed goal is constructed.

3.2.3.2. FP7. Planning

With previous actions defined an analysis on each is required as to address the necessary planning to realize them. The purpose of this is to recognize what requirements, competencies and risks each option carries. With that information in hand all can then be evaluated thus providing support for decision-making on what improvements are feasible to go forward into the next phase to initiate a concrete project development.

- ELI1.Requirements: Starting from the previous defined actions here it is proposed that an analysis of said actions is conducted to determine their requirements for deployment. This will help to contextualize inside the enterprise the need, impact, costs and risks of a future project. These should also contemplate possible constraints across all three dimensions. At this stage of CPPS-3D useful tools are QFD and Axiomatic Design for perceiving requirements and constraints.

- ELI2.Competencies: The intention at this stage is to identify which competencies are needed to execute the desired changes. The enterprise should investigate if their employees already have the necessary desired capabilities that can be used. Or if not, plan for other alternatives either by offering the means to qualify own personnel or to bring expert external suppliers that will carry out the necessary actions.
- ELI3.Priorities and risks: Once the previous elements are settled the last stage before deciding on a concrete project to deploy is to look at all the planned options and evaluate them. Through this it will be possible to study and prioritize risks which in turn will support decision-making. Several aspects are to be taken into account here and at this stage of CPPS-3D for prioritizing risks an appropriate tool is FMEA. This will allow to identify factors that threaten gains and also rate the severity and likelihood of occurrence of said factors, be it technological, organizational, human, economic, political, etc. In addition, at this point project management must also be considered. A project leader and its team must be defined before the development process. Responsibilities and time frames of beginning, planning, executing, controlling and ending the project should be described in project documentation. Project leader should pursue all project goals within given constraints.

3.2.4. CPPS-3D Assessment table guide and radar

To complement the prior descriptions with a visual tool, it was developed an Assessment table guide and radar. The template for this is presented in Appendix I.1.

In it are defined 16 different category-related areas for analysis and gap evaluation. Each area is defined as pertaining to one of the proposed CPPS-3D dimensions and relationships. They intend to serve as a guiding topic for the promotion of discussion between relevant parties in order to evaluate them. Each area is rated from 1 to 5 with that rating depending on its operational and integration capabilities. The ratings are adaptions of all dimensions to the technological concepts of the 5C architecture. This provides a visual aid in determining the current status of the enterprise across the discussed dimensions as well as enable perception on much an improvement can accomplish.

The columns corresponding to Current Status portray the assessment across the defined areas and complements the previous descriptions of the FPs. The Next Goal Vision columns translates the expected benefits of implementing a proposed improvement. As a result, it is then possible to reflect this evaluation in a radar plot for systems comparison. The radar plot has six axis namely the three proposed dimensions and overlapping regions. Data points are calculated by the average of its associated areas and represented by a continuous black line for Current Status and a dotted orange line for Next Goal Vision. The added value of this graphical representation is to develop a common understanding of the status of the enterprise and to recognize the existing gaps or the potential for further developments.

The proposed 16 areas for evaluation are described next. Each area's corresponding rating concepts from levels 1 to 5 are proposed in the respective mentioned Appendix.

- Organizational Dimension (Appendix I.2): These areas are related to functions, responsibilities and principles as well as methods and tools implemented to run and manage an enterprise. They concern to how production is structurally organized and supported by specialized management software, such as Enterprise Resource Planning (ERP), customer involvement in production decisions and effective visual management of processes. The following are proposed as key areas to look at:
    - Organization in production and Support Functions
    - Customer focus and employee awareness
    - Workplace Organization and Visual Management
- Sustainability (Appendix I.3): As the enterprise evolves the organizational changes must accompany the technological changes. New technologies bring forth changes and these changes must be evaluated and controlled to ensure that they continue to add productivity, quality and safety benefits long after their implementation. The following are proposed as key areas to look at:
    - Audit and Control Processes
    - Quality and Safety
- Technological Dimension (Appendix I.4): These areas intend to evaluate how technologically advanced is the enterprise. They look at how technologies improve workers productivity, monitor processes and promote production flexibility as well as support systems vertical and horizontal integration throughout the enterprise. The following are proposed as key areas to look at:
    - Standard Work
    - Reliability and Robustness
    - Processes and affective resources
    - Integration and automation
- Continuous Improvement (Appendix I.5): As automation levels rise up to deal with repetitive tasks the need to rely on humans' knowledge and creativity is further reinforced. These areas assess the way processes can be improved from resorting to human ingenuity. The following are proposed as key areas to look at:
    - Problem-solving
    - Performance improvement
    - Management of improvement ideas

- Human Dimension (Appendix I.6): These areas relate directly to the needs to redefine human roles in the I4.0 environment. They are based on the concepts of Cyber-Human Systems previously discussed and the integration of both workers and managers into the enterprise. The following are proposed as key areas to look at:
    - Versatility / Backup Capacity
    - Role of leadership
- Communication (Appendix I.7): Two relevant areas were chosen here by virtue of the overlapping with the Organizational and the Human dimensions. For the first it is important to have the means to reliably and accurately evaluate how processes perform. As for the second it relates to information availability and sharing, including with suppliers and customers, in order to promote better operation management. The following are proposed as key areas to look at:
    - Performance evaluation
    - Communication for the management of operations

3.3. CPPS-3D Project development phase

After concluding the *Assessment* phase the outcome should a clear set of decisions about what aspects to improve and their priorities. Thus concrete projects can be started and carried onto deployment, hence the second phase of CPPS-3D methodology presented in Figure 3.5. As before each step consists of Focus Points (FP) and Elements of Interest (ELI) required to be completed.

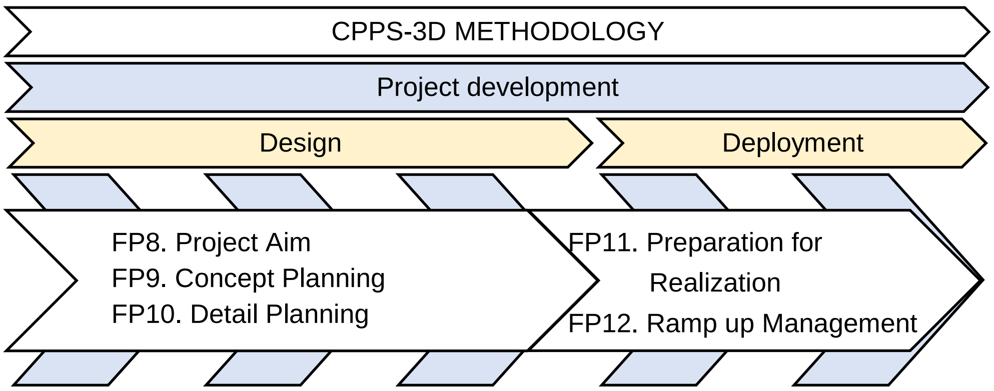


Figure 3.5 - CPPS-3D Project development steps

3.3.1. Design step

Following a decision from the end of the previous phase, to begin this phase a concrete goal must be chosen in order to be more adequately designed, developed and implemented. In practical terms a project team with the adequate competencies should be created to develop and deploy the chosen project. Similarly to before, Table 3.4 presents the expansion of the graphical design of this phase into selected FPs and ELIs for guidance.

Table 3.4 - CPPS-3D Design Step

<table>
<tr><th colspan="3">PHASE: PROJECT DEVELOPMENT</th></tr>
<tr><td rowspan="3">STEP: Design</td><td>FP8: Project aim</td><td>ELI1: Problem and Goals
ELI2. Requirements
ELI3. Targets</td></tr>
<tr><td>FP9: Concept planning</td><td>ELI1. Data-collection
ELI2. Product and Process concepts
ELI3. Design concept and simulation</td></tr>
<tr><td>FP10: Detail planning</td><td>ELI1. Product and/or Process design
ELI2. Product and/or Process analysis
ELI3. Scenarios evaluation</td></tr>
</table>

3.3.1.1. FP8. Project aim

This FP aims at collecting information from the customer in order to establish the basis for defining the project to be undertaken. It consists of:

- ELI1: Problem and Goals: The correct identification of a problem and definition of what is desired to achieve are key issues for defining a project. This requires an overall assessment of feasibility and profitability as well as defining the responsible decision-maker, the project leader and its team. The first step is to make it clear to all involved the importance of the ongoing project. Afterwards a working plan is developed containing identification of the problem, project scope, goals, customers, market, constraints and strategy. Here it's needed to understand the organization context and the customer needs (CNs), i.e. the benefits that are expected by the customer. These are often not clearly defined as in non-technical, non-quantitative wording so searching for their definition can produce further constraints for a project. Constraints can be technical, economic, social, environmental or political limitations imposed to the design solution by the stakeholders. The term stakeholders refers to all individuals and/or organizations that directly impact the project by means of their own input, such as customers, management, suppliers, lawmakers, etc. Constraints state the limitations to project managers and designers of acceptable solutions, may not be independent and their nominal values may be very strict. Correct problem definition allows for appropriate definitions of project strategy, planning, project team and resources. Due to all this at this stage of CPPS-3D the use of Axiomatic Design complemented by the Kano model is essential for success.

- ELI2.Requirements: Following the AD workflow at this stage functional requirements (FRs) are derived from CNs setting the minimum amount of requests that completely characterize the design objectives. Creative and assertive thinking in terms of functionalities is critical here for the success of the project as it is important to assure that no FR is missing. They should be stated in solution-neutral terms i.e. functions to be achieved rather than specific solutions as imagined by the stakeholders. For this denominations consisting of action words/verbs, such as “provide”, “increase” or “decrease” are more appropriate. In addition it is also important to quantify FR’s in terms of a range, i.e., an upper value and a lower value or a toleranced nominal value. A well-documented and prioritized list of FRs is desired to obtain as it will help to keep them current, visible and accessible for evaluation and decision, based on specific criteria.
- ELI3.Targets: Project targets need to be measured relative to the problem they are intended to solve. A quantifiable measurement is necessary to control the purpose of the project. The project leader must always be aware not only of what the problem is but also of the critical importance to develop metrics and specific quantifiable goals. The improvements of a design solution can only be evaluated if they can be measured.

3.3.1.2. FP9. Concept planning

The concept planning is related with the system design or selection to answer to customer needs. It depends if a system is being either designed from scratch or selected from existing proven ones. It involves a set of operations and tasks to be planned and executed. As seen in AD following the definition of Functional Requirements (FR) there is a translation of these into Design Parameters (DP).

- ELI1.Data-collection: A problem well described facilitates the search/development of its solution and enables the definition of DP. Herein it is required that data about the problem context and the systems at work be collected. For this a valuable information resource is describing in terms of functions the engineering systems at play and their problems. As a result, the grounds to undertake an examination of functions and perform a value analysis of products and services is set forth. Inside the project team different ideas can be proposed and analysed in terms of benefits, requirements, customer satisfaction and failure modes to build up internal knowledge. To help fully describing and understanding problems here proper tools are QFD and FMEA.
- ELI2.Product and Process concepts: This conceptualization is based on a functional analysis that establishes the relations of DPs with the corresponding FRs, i.e. which elements of the design object satisfies previously defined FRs. The DPs describe the physical features, i.e. the embodiment, of any design solution such as materials, shape, size, etc. This is a continuation of the AD workflow.

- ELI3.Design concept and simulation: The final step in AD is to correspond DPs to actual Process Variables (PV). These are the actual physical elements of the process that directly satisfy the previously studied and specified DPs. They describe the realization of the design objects. Knowing the DPs and corresponding PVs, a model can be constructed to facilitate analyses that evaluate cost and complexity reduction as well as help to define if a true breakthrough is needed in the design. In view of this, I4.0 technologies can bring great benefits here. With knowledge of processes and relevant PVs it is possible to resort to 3D prototyping and/or simulation of virtual models for testing design concepts. Through this, designs can be verified and improvements can be planned contributing to faster problem-solving and acceleration of innovation processes. At this stage of CPPS-3D several design issues can be found and the TRIZ problem-solving theory can bring forth valuable insights on how to deal with such issues.

3.3.1.3. FP10. Detail planning

Once a product or a system is selected or designed an appropriate evaluation for that product or system is to be defined. Therefore detail planning consists in a set of analysis and evaluations to assure a solutions' operability is consistent with the requirements it will be subject to. To the best of extents the proposed solution must be evaluated as a system integrated with other systems and/or as an extension of other mechanisms.

- ELI1.Product and/or Process design: Continuing from the previous phase, herein the previously chosen architecture(s) starts to be detailed as several options can still exist in the design. Therefore evaluation of possibilities and selection from multiple opinions are required at this stage based on confidence levels and risks, in order to define a final project solution for deployment. Running a simulation or a virtual model through computer simulation can bring great insights and confidence to choices. Once again, at a planning stage VSM and TRIZ are valuable complements for finding and resolving conceptual problems that may persist.
- ELI2. Product and/or Process analysis: This integrates principles and methods to detail critical design characteristics and optimize target values to be achieved. Most notably, the recourse to a simulation or virtual model to test different PVs will guarantee a robust design that ensures the proposed solution is easy to realize and implement. The aim here is to recognize activities that are needed in order to maintain capable processes and to prevent reverting back to past situations or status.
- ELI3.Scenarios evaluation: This serves as preparation and validation for deployment. Based on continuous improvement principles it requires an evaluation with people working together in search of opportunities for present and future improvements, having in mind the capital investments. Through this, design options can be validated and their implementation can be structured and planned. At this stage of CPPS-3D a

risk analysis should also be conducted comprising of risk identification and assessment. Through this analysis, particular risks are investigated in terms of probability of occurrence and severity of effects based on concrete data previously obtained and registered by the enterprise. This further enforces the absolute necessity of the enterprise to keep written records of its processes for support of future decisions. Otherwise, when these do not exist risk analysis is reduced to more fallible decision-makers own judgements.

3.3.2. Deployment step

The final step of the methodology includes the actual deployment of the solution and its monitoring as to properly manage its ramp up period up to full production. After fully implemented and integrated with the other systems present, continuous monitoring of performance will allow for the evaluation of benefits and planning of future improvements. For deployment the conceived FPs and corresponding ELIs are presented in Table 3.5.

Table 3.5 - CPPS-3D Deployment Step

PHASE: PROJECT DEVELOPMENT		
STEP: Deployment	FP11: Preparation for realization	ELI1. Planning evaluation ELI2. Implementation tests ELI3. Test analysis
	FP12: Ramp up management	ELI1. Installation ELI2. Reconfiguration and improvements ELI3. Evaluation and further progress

3.3.2.1. FP11. Preparation for realization

Deployment begins with a focus on making the necessary preparations before actual implementation. For this it is proposed the following ELIs that consist in dealing with all the necessary work and diligences required to actually deploy the designed solution ensuring that it can be done as efficiently as possible.

- ELI1.Planning evaluation: Beforehand it is important to determine how to evaluate implemented changes to processes so that expected results may be compared to actual obtained results. For this an evaluation plan should be formulated outlining relevant details such as concrete variables and metrics (KPIs), methods for data collection, responsibilities, timeline, costs and expected results. Through this conceptualization it is then clearly defined how to measure implementation of introduced changes as well as possible outcomes.

- ELI2.Implementation tests: Prior to committing to full implementation, initial tests should be conducted to detect unseen constraints, requirements and problems. From this prototypes can be generated and improved, allowing for further enhancements of designed solutions. Establishing parallel systems (see Migration Strategies in Chapter II) also allows for testing and validation of correct systems operation. Before the tests are initiated backups of the current systems must be done to allow for rollback in case introduced changes cause unexpected failures. During testing previously determined data collection methods should also be tested regarding their feasibility and importance.
- ELI3.Test analysis: After testing is completed the designed solution can be reviewed in terms of results and adjusted as deemed necessary. At this stage of CPPS-3D an analysis through VSM can be executed to observe work flow. It will serve as a fundamental support pillar for management/decision-makers to judge whether or not the final implementation of a change will go forward.

3.3.2.2. FP12. Ramp up management

In production the ramp-up period typically comprises the works and time needed to take production from its initial stages all the way up into full output levels. Starting from test units the enterprise develops confidence in its own processes and abilities, as well as those from its suppliers, to steadily and consistently increase production to target levels of volume, cost and quality. This is a crucial stage for success and specialised ramp-up management can be a deciding factor in quickly identifying and solving unexpected problems present in full scale production. This way efficient and effective ramp-ups can be conducted [61]. From these concepts the following ELIs were established:

- ELI1.Installation: The actual installation and setup of new equipment and software should be carefully planned logistically. This will allow to be quickly executed and avoid unnecessary delays on production. Use of 5S and SMED methods are important in the preparation of works. Once the new solution is installed and ready to be used initial preproduction tests are ran to detect discrepancies between previous prototypes testing and real production conditions.
- ELI2.Reconfiguration and improvements: This stage will deal with the actual differences in real production environments which only when the new system is actually in use can processes be adjusted and fine-tuned for efficiency. The introduction of a new system will also allow for reconfiguration of interconnecting systems and consideration of possible improvements. Through this actions it will become possible to increase production volume up to target levels. At this stage of CPPS-3D useful tools to implement are the establishment of records by means of Histograms and Control charts. In addition other techniques such as TPM, SMED and Poka-yoke can contribute to operational improvements and better efficiency.

- ELI3.Evaluation and further progress: Once the new designed solution is in place and fully running, data collection and analysis allows for the evaluation of results. These should be in line with the targets previously defined or else reasons of failing to meet the intended goals must be investigated. The continued registration of collected data allows for the creation of histograms which then become useful tools for further analysis overtime. A defining characteristic in CPPS is also their always advancing technological innovation so management should also create the means to regularly be updated on new and improved technological solutions.

In conclusion, CPPS-3D is a methodology that intends to help and guide enterprises in identifying gaps and deploying solutions to fulfil such gaps. It mainly consists of two main distinct phases namely the Assessment and the Project development.

In the Assessment phase the level of development and the conditions for the enterprise to carry out I4.0 are described and qualitatively rated. This evaluation of I4.0 readiness is based on three fundamental and inseparable dimensions of I4.0, namely the Organizational, the Technological and the Human. Common intersection areas between them that further allow to characterize the enterprise are also defined. Those areas are the Sustainability, Communication and Continuous Improvement.

In the Project Development phase a particular problem is focused on and the stages for designing and implementing a solution for it are sequentially tackled. Going through the several FPs requires strategic thinking, customer input, technical discipline, expertise knowledge, creativity, speed and innovation to ensure a successful output. For this, Axiomatic Design and the Kano Model are useful in determining customer needs and translating them into technical details, but other tools are also recommended along the way to deal with different potential problems that may arise at different stages.

As a whole CPPS-3D guides enterprises through the procedures necessary to systematically and continuously analyse their existing systems, find their gaps, design solutions and then develop them. In practical terms, first it allows to decompose the assessment and analysis of complex systems into smaller systems with no disregard towards their interconnectivity. Afterwards it then provides an appropriate framework to lead enterprises from design to deployment of improvement solutions by deconstruction of tasks.

Chapter 4.

Case study synthesis and discussion

This chapter presents the application and usefulness of the CPPS-3D methodology. It was tested and validated in a real case study related with a leading Portuguese manufacturer of metal-based solutions and products. Through it a new visual management system with real-time data collection and sharing was developed to respond to an identified gap.

4.1. Case study synthesis

An application of the CPPS-3D methodology was explored by means of a case study at a leading Portuguese manufacturer of metal-based solutions and products. This enterprise has over 60 years of experience and its business areas include the automotive, the transportation, the industry, the tooling and the solar markets.

One of its newer production sections contains three robotic welding cells (Figure 4.1). Parts are manually loaded and unloaded into rotating tables by workers to feed the robots. Production data is automatically collected and sent to the ERP system. Meanwhile at the shop floor there is very little information available in real-time or even in near real-time about current production. This shortcoming was observed by the enterprise who then reached out for solutions. They intend to add to this section means to enable real-time production data and statistics visualization capabilities. They also wish that such information should be personalized according to different users at the shop floor as well as be accessible both in location and remotely.

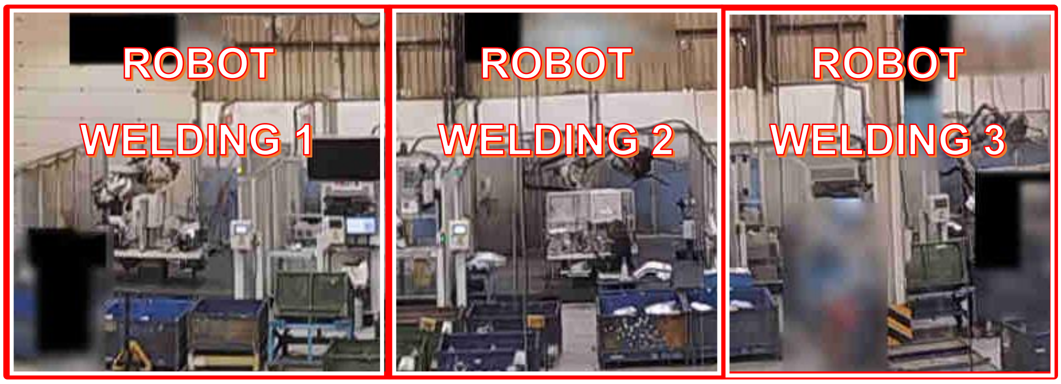


Figure 4.1 - Robotic-welding section

This was perceived as an opportunity to test CPPS-3D methodology in a real production environment. CPPS-3D is composed of two distinct phases (Figure 4.2), namely the Assessment and then the Project Development.

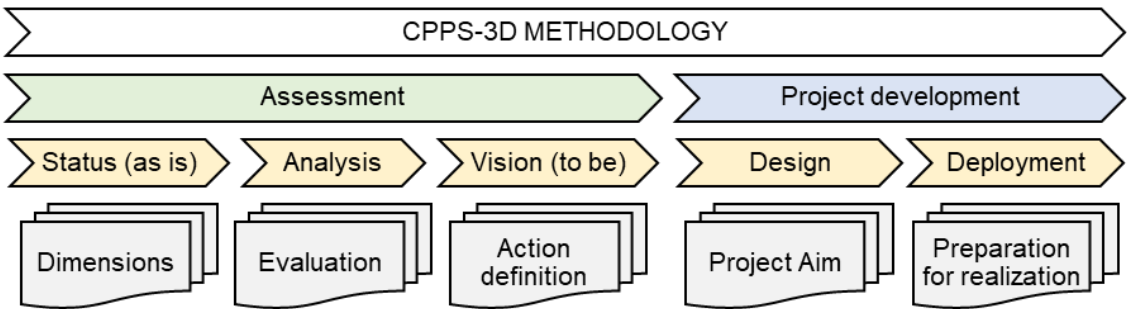


Figure 4.2 - CPPS-3D overview

4.1.1. Case study Assessment

In the Assessment phase it is described the current status and a next goal vision. This is done by going through all Focal Points (FP) pertaining to this phase's Steps (Figure 4.3). Afterwards the gathered information is complemented visually.

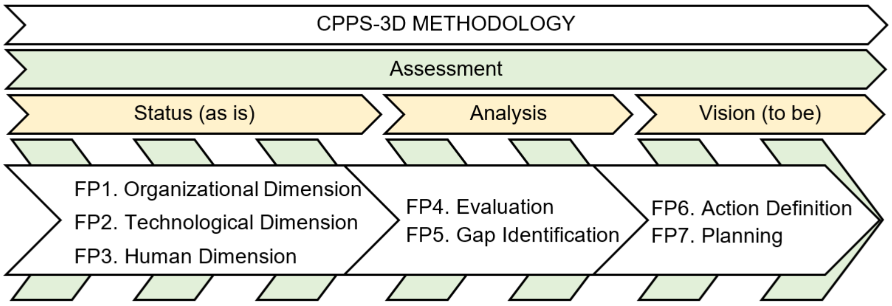


Figure 4.3 - CPPS-3D Assessment workflow

As requested by the customer, the Assessment was conducted targeting only the specified production section and did not take into account other connecting production systems. Due to time constraints there were limitations on current status analysis as some aspects had to be estimated in accordance to spoken information at meetings rather than observed in loco.

To follow up on its iterative nature, after Project Development is concluded, a new Assessment should be conducted at least on this section to identify new improvement opportunities and promote continuous improvement. Furthermore, new future Assessments should gradually start to include adjacent production sections. From these recurring actions eventually the Assessment will scale up until it covers the whole enterprise.

The first step of CPPS-3D is Status and it contains the Elements of Interest (ELI) previously presented in Table 3.1. The following topics cover those.

4.1.1.1. FP1. Organizational dimension

The first element to look at is ELI1.Product. This particular production section receives metal parts that workers manually load into rotating tables. The tables are fitted with fixtures to hold parts in the correct position for robotic arms to proceed with the spot welding after table rotation. After the welding is finished the tables rotate back so workers can take out the finished parts and load new ones before being loaded into pallets to be transferred to the next section. Due to, in this case, the product being already defined and in full production no QFD nor were FMEA studies conducted.

In terms of production processes (ELI2.Processes) this section relies on human workers loading and unloading parts as well as transporting them to and from the section. Production data is collected by PLC controller and sent to the ERP system for collection of production KPIs. This makes it difficult to perceive real-time data on the shop-floor and is indicative of a low level of integration of the section.

As far as ELI3.Value chain concerns, due to time constraints no VSM was made available to better help identify non-value activities. Nonetheless the production section was observed in loco and noted that sometimes production stops and managers don’t know immediately why (malfunction, busy resource, piece shortage, etc.). This implies that this production system is slow to respond to disturbances and its performance isn't feeding information in real-time back into the value chain. From this it is concluded that setting up a visual management system on the shop floor, as initially requested by the customer, could indeed bring immediate benefits.

4.1.1.2. FP2. Technological dimension

Starting by ELI1.Production equipment it was observed that automated tasks are controlled by PLC and executed by welding robots and rotating tables. On the other hand, the system relies heavily on human workers to perform the tasks of manual loading and unloading of parts as well as transport.

As discussed, a vital point of I4.0 is collection and communication of accurate and reliable data from all production elements. At present time only machines communicate upstream to the ERP system (ELI2.Support systems). This means that information about this production section is not fully characterized nor immediately accessible. This situation is not useful for decision support for shop floor managers. Once again this advocates the need to implement a visual management system at shop floor level to enable better operation management and therefore a higher level of production flexibility.

As for ELI3.Integration level at present the section is integrated only vertically with other systems by virtue of the ERP system.

4.1.1.3. FP3. Human dimension

Beginning with ELI1.Function and levels it was observed that the workers at the section work exclusively at that section. Their functions are mostly decomposed into routine standard work, apart from small cleaning and maintenance tasks. They rotate functions on a regular basis.

As for ELI2.Competencies adequate training into the functions was required for workers to correctly execute tasks. There are no visual aids to executing functions. Workers from other sections can’t substitute them as those do not possess the necessary knowledge of tasks.

The section is managed by a global production supervisor with the daily production plan being communicated to workers at the start of the shift (ELI3.Leadership).

The second step of CPPS-3D is Analysis and it contains the Elements of Interest (ELI) previously presented in Table 3.2. The following topics cover those.

4.1.1.4. FP4. Evaluation

To complement all the previously acquired information, the assessment guide table presented in Appendix I can be utilised as a mean to realize the ELI1.Measurement diligences. With it several categories pertaining to all discussed dimensions are analysed and a rating assigned.

In ELI2.Dimension profile the enterprise considers it-self globally as stable and predictable with strict established rules. However certain business areas are internally encouraged to be more innovative and risk-taking to promote adaptability and experimentation of new ideas.

Given the small scope of this work, limited to a particular production section, no analysis of ELI3.Business model was carried out.

4.1.1.5. FP5. Gap identification

The Assessment results indicate that there is a necessity for real-time data on the shop floor in order to better manage the section and provide support to identifying wastes and improvement opportunities. Looking at ELI1.Qualification and training the enterprise does not have the human resources to implement an advanced visual management as they want. For that an outside team must be brought in with the necessary technological skills and knowledge. Afterwards human resources will have to be trained into the use of the new system.

For ELI2.Equipment and processes currently machines communicate only with the ERP system. A solution must be found to communicate with machines and the ERP in order to make available production data on the shop floor in real-time.

Regarding ELI3.Organization methods, this section is managed by a global supervisor. Since there’s no information available in real-time and no section managers this once again implies that production is prone to be affected longer due to disturbances because of lack of information for swifter reactions.

The third step of CPPS-3D is Vision and it contains the Elements of Interest (ELI) previously presented in Table 3.3. The following topics cover those.

4.1.1.6. FP6. Action definition

Having settled with the customer that a new advanced visual management system is a priority the methodology advances by defining the means to realize it. Starting with ELI1.Product-service the first thing to do is define customer needs and from there design the new system. For this the Axiomatic Design methodology and the Kano model are useful tools.

In ELI2.Processes it was identified that the production process does not need to be redesigned for the chosen goals and can be just complemented with new sensing and communication equipment. As for the organizational way of being the new system will only imply retraining into new technologies. As a benefit the new system will allow to assign a new local manager to the section whose decisions can be remotely supported by other managers.

Lastly considering ELI3.Resources, for the new system additional resources are needed in terms of technology, namely for establishing communications between systems and additionally for data processing and visualization. Human resources will internally be trained into the new systems after an external team implements it.

4.1.1.7. FP7. Planning

In the absence of one, a visual management system on the shop floor will impact positively production with expectations of better performance analysis, production flexibility, improved productivity and reduced maintenance (ELI1.Requirements). The new system will require integration with the ERP software for access to all the production network. Additionally mobile devices will need to be made available to designated users.

As for ELI2.Competencies the enterprise has currently no qualified human resources to develop and implement such system on its own. Because of that an external team has to be brought in for development of the new project.

Finally assessing ELI3.Priorities and risks the enterprise feels that implementing a visual management system at the entire shop floor is a priority. This production section will serve for testing a new solution and if the results are good it will be expanded to other sections. In terms of risks this is intended to integrate an advanced technological solution into an existing production system without disturbing current production. This implicates a small risk and medium time-frame of around 2 years to fully deploy a solution. In addition, proper project management is vital. In that sense a project team was formed in order to take a solution from beginning to end.

4.1.1.8. Assessment guide table and radar

Complementing this evaluation it was produced the Assessment table guide presented in Table 4.1. As described before, each category is rated from 1 to 5 with that rating depending on its operational and integration capabilities. The ratings are adaptions of all dimensions to the technological concepts of 5C architecture. By assigning these ratings it was possible to construct the radar in Figure 4.4. It offers visual aid in determining the current status of the enterprise across the discussed dimensions represented with a black line and enable perception on how much the improvement can accomplish represented with a dotted line.

Table 4.1 - Enterprise assessment table

(Enterprise Name) Date: 2019/09/19		CURRENT STATUS		NEXT GOAL VISION	
CPPS-3D		**LEVEL**	**COMMENTS**	**LEVEL**	**OBJECTIVE**
ORGANIZATIONAL DIMENSION	Organization in production and Support Functions	1	Production cells linked to ERP, no real-time data on shop floor	3	Real-time production system information available anywhere
	Customer focus and employee awareness	1	Product manufactured per customer previous specifications	2	Production data available to customer at location
	Workplace Organization and Visual Management	1	5S implemented, Andon lights on shop floor	3	Automatic targeted notifications to users
SUSTAIN-ABILITY	Audit and Control Processes	1	KPI generation by ERP, no real-time information at shop floor	3	Targeted production information available remotely in real-time
	Quality and Safety	2	Use of automation for repeatibility. Physical barriers in robotized cells.	2	Automation for repeatability. Physical barriers to automated hazards.
TECHNOLOGICAL DIMENSION	Standard Work	2	Standard work documented, section workers rotate functions	2	Documented standard work procedures. Section workers rotate functions.
	Reliability and Robustness	1	Data collected sent to ERP, no real-time data on shop floor	3	Production system monitoring, analytics for historical data of similar machines.
	Processes and affective resources	1	Section fragmented from enterprise, no resource sharing	2	Resource sharing across sections, Common technological standards.
	Integration and automation	1	Vertical integration with ERP, PLC control of production cells	3	Horizontal integration of processes, central hub server for real-time remote data access
CONTINUOUS IMPROVEMENT	Problem solving	1	ERP data analysis by in-house processes experts	2	Real-time production information available
	Performance Improvement	1	ERP data collection	2	Real-time production information available
	Management of Improvement Ideas	1	Ideas shared through hierarchical structure	2	Promotion of open sharing and discussion of ideas
HUMAN DIMENSION	Versatility / Backup Capacity	1	Workers of this sector rotate functions only in this sector	2	Training across different production sections
	Role of leadership	1	Hierarchical management with traditional top-down structure	4	Focus on workers, Creating acceptance for change, Counteracting organizational inertia
COMMUNI-CATION	Performance evaluation	1	KPI analysis by top management, worker's evaluation by supervisors	2	Remotely available production system information in real-time
	Communication for the management of operations	1	Information flow through managerial hierarchy	3	Remotely available production system information in real-time

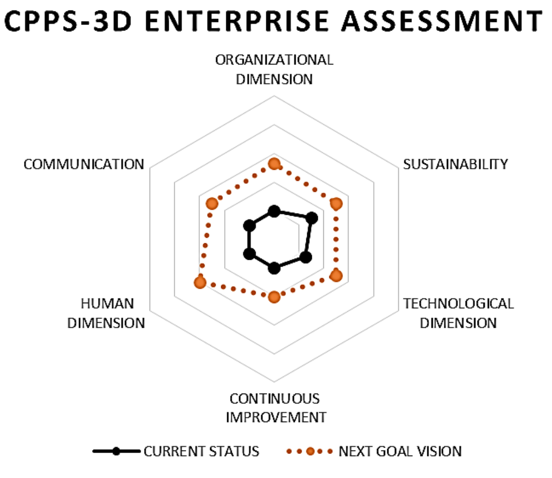


Figure 4.4 - CPPS-3D enterprise assessment radar

By implementing a new visual management system on the shop floor and allow for it to have remote communications capabilities top management intends to improve the section's current situation throughout all dimensions. Organizationally it will support faster decision-making and better production management. Technologically it will provide more accurate and reliable data available anytime and anywhere. In the Human dimension it will promote a more dynamic workplace promoting participation from both workers and managers in the production processes. Given the Assessment results and the initial proposed challenge the enterprise decided to go ahead and work together with us. Their expectations pointed towards finding a feasible technological solution to implement visualization in real-time of production data at the shop floor. Committing to that the Project Development phase of CPPS-3D was initiated.

4.1.2. Case study Project Development

In the Project Development phase a concrete improvement project is brought from design up into deployment. Again, this is done by going through all Focal Points (FP) pertaining to this phase's Steps as in Figure 4.5.

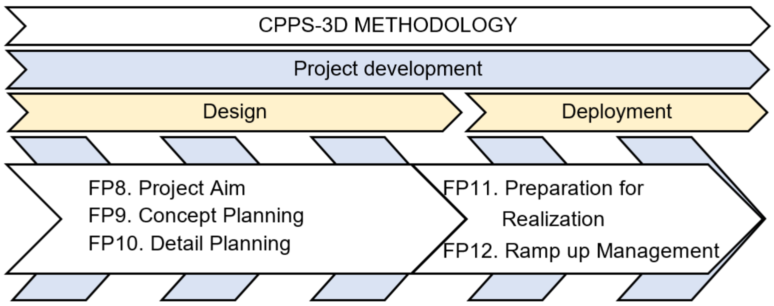


Figure 4.5 - CPPS-3D Project Development workflow

The project goal is to realize an advanced visual management system.

Despite of the existing ERP system, currently there's no available nor accessible information on the operational performance of machines and cells with a level of detail and time periods that can support immediate analysis and decision making at the shop floor. By addressing this issue management wants to enable collection and immediate availability of production data to support analysis and shop floor decision-making on operational aspects.

The new system must retrieve performance data from the section's production cells, convert it into easy to understand information and then make it available on the shop floor. That information should be presented in (or near) real-time to different users and dependent on their specific roles and responsibilities. Additionally, it ought to resort to mobile devices, e.g. smartphones and tablets to use as mobile HMIs.

At the end of the project the main objective is to have an omnipresent system that can detect users near the production cells and prompt them appropriate and relevant information.

The fourth step of CPPS-3D is Design and it contains the Elements of Interest (ELI) previously presented in Table 3.4. The following topics cover those.

4.1.2.1. FP8. Project aim

Proceeding into ELI1.Problems and Goals and as decided in 4.1.1.6, the principles of Axiomatic Design and the Kano Model were used to identify Customer Needs (CN):

Must-be attributes (the bare minimum capabilities of the new system):

- CN1: Obtain key indicators per production cell and per line
- CN2: Display production data in real time at the shop floor

One-dimension attributes (expected by the customer):

- CN3: Identify user and respective access level
- CN4: Present different indicators according to user's access level

Attractive attributes (added benefits of the system)

- CN5: Display information in a friendly, proactive, non-intrusive way
- CN6: Allow management to access data remotely

Next the ELI2.Requirements follows. For that CNs are used to derive the following Functional Requirements (FRs) to satisfy each CN:

- CN1: Obtain key indicators per production cell and per line
    - FR1: Acquire data from existing controllers (analogue and digital of machines and other adjacent systems like jigs, buffers, etc.).
    - FR2: Use of a modular solution that allows adding new sensors and measuring devices
- CN2: Display production data in real time at the shop floor
    - FR3: Analyse acquired data to produce contextualized information
    - FR4: Interact with the multiple machines with single interface
    - FR5: Store acquired data
    - FR6: Represent data with text and graphics
- CN3: Identify user and respective access level
    - FR7. Identify user access to the system
    - FR8. Assign access level to user based on function (worker, manager, etc.)

- CN4: Present different indicators according to user's access level
    - FR9: Hierarchize data relative to its importance (type, access level, alerts, deviations, etc.)
- CN5: Display information in a friendly, proactive, non-intrusive way
    - FR10. Detect user's proximity
    - FR11. Activate display on user order
    - FR12. Communicate in real time
    - FR13. Use mobile devices for information display
- CN6: Allow management to access data remotely
    - FR14. Access data via the Internet

Based on these, the proposed solution involved acquiring data from existing controllers and the ERP, detect a user's proximity and on command display information on a user's mobile device. For this the following possible constraints were taken into account:

- Existence of ERP software: The ERP collects production data from the shop floor so with a proper Application Programming Interface (API) that data can be relayed to mobile devices for a custom developed HMI. This is useful for accessing historical production data and also integrate the new system into a central hub of information.
- Physical space at shop floor: The shop floor area to be intervened has very limited space available so any solution has to take that into account. The choice of use of mobile devices as portable HMIs is directly influenced by this.
- Possible radio signal interferences at the shop floor: Tests were conducted to investigate if Bluetooth communications were effective on the shop floor or if there were limitations. No problems were found and the use of Bluetooth is possible.
- Physical limitation of workers: At the present time workers at that area have no physical limitations that would impair them from using the new system.
- Availability of mobile devices to the users: Mobile devices such as smartphones and tablets will be handed out by management to designated users.

After consideration of these, ELI3.Targets was approached with the intention to develop metrics and specific quantifiable goals. This will enable to later evaluate the work done and provide insights on how the new system is performing and how it can be further improved. As a start point, but subject to later be revised before deployment, two goals were set:

- Three levels of access to information namely workers, managers and executives
- Three different information KPIs per access level (to be defined later which ones by customer)

4.1.2.2. FP9. Concept planning

For ELI1.Data Collection the current systems at play were analysed together with the customer to discuss possible technical solutions. The proposed final solution decided upon is based on three key components:

- Smart Object: a microprocessor physical interface with own processing and communication capabilities, designed for data acquisition from current machines, communication with ERP and with expansion possibilities.
- HMI model: a software framework designed to build a HMI layer to be used as an application on mobiles devices
- Beacon: a Bluetooth Low Energy (BLE) device that broadcasts their identifier to nearby portable devices allowing for these devices to act upon in close proximity to the beacon. BLE was preferred as it consumes less energy because it emits pulse signals at regular intervals as opposed to Bluetooth standard which emits a continuous stream of data.

Figure 4.6 represents the proposed solution.

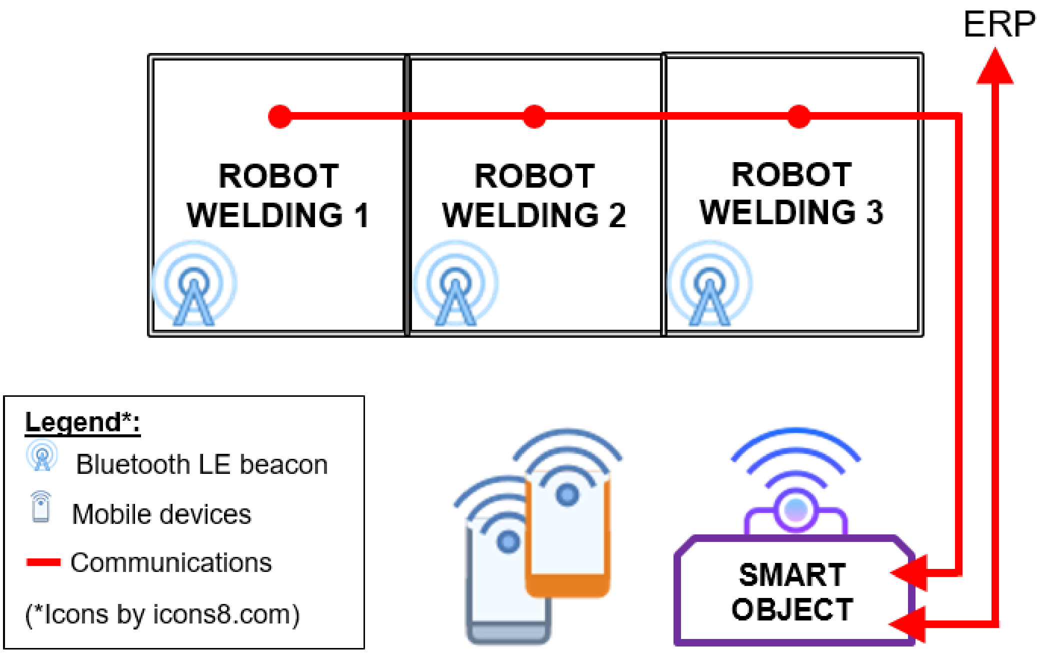


Figure 4.6 - Proposed system configuration

With this configuration set in mind and moving into ELI2.Product and Process concepts, each identified FR was mapped to the necessary Design Parameters (DP). These are the required solutions to fulfil FRs and are as follow in Table 4.2.

Table 4.2 - FR-DP mapping

Functional Requirements (FR)	Design Parameters (DP)		
	Smart Object (data acquisition, processing, communication)	**HMI model (layer as mobile device application)**	**Beacon (user proximity detection)**
FR1: Acquire data	DP1: Communication with existing controllers and ERP		
FR2: Modular solution	DP2: Expansion capabilities		
FR3: Analyse data	DP3: Local data processing algorithms		
FR4: Multiple machine interaction	DP1: Communication with existing controllers and ERP DP4: Wireless communication		
FR5: Store data	DP5: Local data storage		
FR6: Represent data		DP6: Visualization tools	
FR7. Identify user	DP4: Wireless communication	DP7: List of users	DP4: Wireless communication
FR8. Assign access level		DP8: List of types of users and access levels	
FR9: Hierarchize data	DP3: Local data processing algorithms		
FR10. Detect user proximity	DP4: Wireless communication		DP4: Wireless communication DP9: Beacon scanning
FR11. Activate display	DP4: Wireless communication	DP7: List of users	
FR12. Real-time communications	DP1: Communication with existing controllers and ERP DP4: Wireless communication		
FR13. Use of mobile devices	DP4: Wireless communication	DP6: Visualization tools	
FR14. Access via Internet	DP1: Communication with ERP	DP10: Remote access tools	

Next ELI3.Design concept and simulation can be tackled. This means identifying the Process Variables (PV) to work which are mapped in Table 4.3.

Table 4.3 - DP-PV mapping

Design Parameters (DP)	**Process Variables (PV)**
DP1: Communication with existing controllers and ERP	PV1: ERP communication API (to be made available from customer) PV2: Existing controllers communication APIs (to be made available from customer PV3: Relevant operating KPIs per cell/user (to be defined by customer, e.g. type of products in line, WIP pieces, operations duration, etc.)
DP2: Expansion capabilities	PV4: OPC-UA (open machine-to-machine communication protocol) API
DP3: Local data processing algorithms	PV5: Currently available machine operating variables (and others to be defined by customer) PV6: Environmental variables (new sensors required for Temperature, Noise) PV7: Event priority list (to be discussed with customer)
DP4: Wireless communication	PV8: Bluetooth Low Energy (BLE) standard PV9: Wi-Fi standard
DP5: Local data storage	PV10: SSD hard drive (capacity to be defined by customer)
DP6: Visualization tools	PV11: HMI model graphical representation module PV3: Relevant operating KPIs per cell/user (to be defined by customer, e.g. type of products in line, WIP pieces, operations duration, etc.) PV5: Currently available machine operating variables (and others to be defined by customer) PV6: Environmental variables (new sensors required for Temperature, Noise)
DP7: List of users	PV12: Number of users (to be defined by customer) PV13: Identity of user (to be defined by customer) PV14: Personal Information per user (to be defined by customer) PV15: Work shift (to be defined by customer) PV16: HMI model login module
DP8: List of types of users and access levels	PV17: Types of users (e.g. worker, manager, CEO, maintenance, etc. – to be defined by customer) PV18: Information access levels (to be defined by customer) PV19: HMI model “User functions” module
DP9: Beacon scanning	PV20: Signal frequency PV21: Signal intensity
DP10: Remote access tools	PV22: HMI model remote access module PV1: ERP communication API (to be made available from customer) PV9: Wi-Fi standard

With the definition of all DPs further testing on location was conducted to test technology and re-check previous identified constraints. This also enabled initial software simulations as proof of concept.

4.1.2.3. FP10. Detail planning

With satisfactory results from initial testing the chosen architecture started to be detailed with the development of the Smart Object and the HMI model.

Due to its simpler nature the Beacon was developed as a separate piece instead of integrated into the Smart Object to allow for its faster development.

Meanwhile due to customer delays on deciding factors the current project is at the ELI1.Product and/or Process design stage. The Smart Object is currently a prototype and its full development is dependent on the customer providing their APIs for communications.

The HMI model (codename *smartHMI4I4*) was developed by a software team and was field tested with good results. BLE beacons were placed at the entrance of each cell to differentiate which HMI (mobile device) to activate according to the user and its proximity. The application locates the user by finding the strongest and nearest beacon signal and then prompts that user with relevant information [62].

At the current time the project only awaits further developments from the customer on the final definition of users, access levels and KPIs, as well as making their APIs available in order to finalize the work done so far. Once these tasks are carried out all components can then be fully completed, tested, analysed, evaluated and possible alternative scenarios studied of its integration into the production system (ELI2.Product and/or Process analysis and ELI3.Scenarios evaluation).

Only after that is successfully concluded can the fifth and final step of CPPS-3D (Deployment) be initiated to pursue Elements of Interest (ELI) previously presented in Table 3.5.

4.2. Case study results and discussion

This collaboration with a leading Portuguese manufacturer further reinforced the perception that Portuguese enterprises aren’t ready for the evolution into I4.0. Even though it is considered a market leader, during this collaboration it was perceived as an enterprise where a traditional organization structure is still very much a fact with little flexibility and adaptability to external factor’s variations such as materials availability, fluctuating prices or customer demand. However because of the ever increasing market aggressiveness top management is starting to feel the need to start looking for innovative ways to deal pre-emptively with problems instead of the currently established firefighting mentality.

But while top management is changing their attitude and promoting changes, along the development of the proposed solution a great deal of resistance to change was felt from within with constant delays of workers and lower management in providing necessary elements. This can be indicative that a fear of change by personnel is still very present. Workers in general appear to fear the loss of their routine tasks to machines and are reluctant to the introduction of new technologies that allow for a more strict control and evaluation of their performance. This also has repercussions into lower management as they perceive that introduction of new technologies is beneficial to the enterprise but new responsibilities will fall upon them, on top of their already overwhelming existing ones.

This mindset is believed to be what ultimately caused project deployment to be continuously delayed. These type of situations can all be seen as evidence that the much desired transition is not an intuitive nor easy process to carry out and enterprises are not ready for it in any of the three dimensions: Technological, Organizational and Human.

Nonetheless the application of the methodology can be considered a success because it allowed for a good assessment of the production section in analysis, the identification of a gap and the development of a solution.

The assessment, although only applied to one specific production section, allowed to obtain an exhaustive report across many areas and grasp a general understanding on how the enterprise functions. This comprehensive description was then coupled with the visual assessment table guide to better understand and identify possible gaps and establish future goals. At the end of the assessment phase the enterprise was well characterized in terms of future possibilities and the selection of improvement actions came naturally as a result.

The assessment phase however, given its in-depth analysis revealed itself to be very time consuming. This proved to be a small setback as the enterprise wasn’t internally well organized in terms of processes and information-sharing and lead into some delays.

In the second phase of CPPS-3D the development of a proposed solution was guided through its different stages and enabled to define and organize teams and tasks. In relation to tools, Axiomatic Design and the Kano Model proved to be valuable tools in establishing a systematic approach into defining a concrete solution. This allowed for better project management and a more expedite initial development. This phase’s delays however allowed to better recognize the importance of team leaders and how that choice of roles must be better scrutinized in future projects.

Overall the application of the methodology to this concrete application was successful and once the new visual management system is fully operational the expected benefits will include faster decision-making, better production management, more accurate and reliable data availability as well as the promotion of a more dynamic workplace with improved reactivity to problems.

Chapter 5.

Conclusions and future work

This chapter presents the dissertation’s conclusions and proposals for future work.

5.1. Conclusions

In order to retain its competitiveness in today's aggressive markets, enterprises need to change their fundamental ways of being and acting. It's widely accepted that CPPS are the correct approach to accomplish this by means of collection and sharing of information and knowledge. The expected benefits are optimization and customization of production that will lead up to batch sizes of one at mass production prices, dynamic business and engineering processes, as well as work-life balance of workers and competitive high-wage economies. To ensure all this, any (re)evolution into I4.0 must take into account the Organizational, Technological and Human dimensions.

It can be found in literature some maturity models for I4.0 each with its own assessing framework and where, in their own ways, each proposes their own dimensions and fields of application. However, it is perceived that manufacturers are, for the vast majority, unprepared to deal with complex models. Additionally, most times top management have unrealistic expectations of what can be achieved at the current time. From this it is believed that there's a necessity for a simpler and concise assessment of necessities.

Organizationally CPPS will promote horizontal integration throughout all the value chain, from suppliers to enterprise to final customer. To obtain this integration, management needs to start developing strategic migration paths into I4.0 in order to gain better knowledge of its own processes and resources. Adapting its more traditional top-down structures into a culture of experimentation, risk-taking and collaboration is a step in the right direction. Additionally, promoting acceptance for internal changes is also a must needed effort to steer into the future path of success and competitiveness.

Technologically enterprises are still very much dependent on its vertical integration of processes through a traditional automation pyramid. This makes it more difficult to share resources across all production and does not promote knowledge-sharing. CPPS promote a decentralized automation architecture and data analysis systems for decision support. This enables more flexibility in production and gains in response capabilities to external variables such as market demand or suppliers performance.

Finally as CPPS evolve and take over the routine tasks and decisions humans will be left with the vital creative roles of handling exceptions and complex issues. This implies requalification of human workers at all levels as well as resorting to new technologies, such as AR and VR, to better assist and guide them in their tasks and training of new roles.

Therefore a methodology to facilitate and guide enterprises and all theirs stakeholders into CPPS was definitely a need to address. Bringing forth a component of originality in its approach, CPPS-3D attempts to reduce complexity by streamlining tasks. It comprises of an Assessment that defines the essential categories to look at and complements it visually, followed by the inclusion of a Project Deployment framework for solution design and implementation.

Although CPPS-3D was only validated through its use in a small production section and on a limited time-frame, applying it to a real production environment, this experience allowed to ascertain some of its benefits and inconveniences. From the gathered results it was concluded that CPPS-3D is applicable not only to a single production section but also its application should be scalable to include several sections or even the whole of the enterprise.

The Assessment phase allows to compile extensive and comprehensive information about several aspects within all three proposed dimensions. By consideration of all three, CPPS-3D allows to better identify gaps, prepare and prioritize improvement projects, serve as decision-making support tool and establish relationships of trust with the customer as the work develops.

However the Assessment phase can be time consuming if the enterprise isn't internally well structured and prepared for information collection and sharing across all its departments. Due to this aspect the assessment should be conducted only when all participants understand the fundamental basic principles of I4.0 across all dimensions. Otherwise external consulting and awareness group meetings are fundamental pre-requisites for the success of CPPS-3D.

In the Project Development phase it was demonstrated the importance of the proposed methodology to support project design and development. Furthermore, Axiomatic Design and the Kano Model were valuable tools to develop a CPS solution to a real problem. CPPS-3D allowed to systematically decompose the new system design into smaller systems with no disregard towards their necessary interconnectivity. With this it was provided the necessary support to project teams for defining roles, responsibilities, time-frames and system's characteristics. Other tools included in the methodology, such as TRIZ, weren't used for this particular case study but are added-value for future applications.

A major difficulty in attempting to deploy the proposed solution were the constant delays on the customer's side in providing much necessary data. It is believed that this was caused by poor management on the part of the customer's team. Nonetheless valuable insight was gained on the importance of correctly selecting team members and leaders and how that process must be better handled in future projects.

Overall CPPS-3D gives a thorough description of the current status of a production system and then provides guidance from the initial stages of solution designing up until deployment and full production. For this CPPS-3D can become a very much needed tool to help guide unprepared enterprises into I4.0 by granting them the knowledge to perceive new technologies contributions and the means to implement such desired transition. In that sense and looking back at the initial research questions answers are now able to be provided.

- What is the level of preparation of enterprises for transition into I4.0?

The transition is not an easy path. It involves looking simultaneously at the Organizational, Technological and Human dimensions of I4.0 to perceive its benefits and requisites. Portuguese enterprises are in its majority SMEs and most only managed by their founders (or immediate family) with no higher education. This means that generally speaking enterprises lack the necessary skills and knowledge to undertake by themselves the long transition process into the I4.0 industry paradigm and are therefore unprepared.

- What contributions can new technologies bring to enterprises?

New technological and computational capabilities bring forth the emergence of Cyber-Physical Production Systems. With integration of physical processes into communication and computational networks then data collection, sharing and analysis can become a vital part of the enterprise bringing forth better supported and informed decision-making. This in turn enables that standard and routine tasks are relegated to automation and empowerment is given to humans where they can excel in problem-solving thanks to their innate creativity skills.

- How can enterprises be better assisted and guided in this (re)evolution?

In responding to this CPPS-3D methodology was developed. It aims at better help and guide enterprises and their leaders in evaluating their capabilities, find gaps, develop improvement actions and implement solutions. CPPS-3D is a framework that facilitates designing, development and deployment of key improvements.

5.2. Future work

The assessment guide table adopts 5C architecture concepts to rate each category. They are intended to serve merely as a guideline and as discussed in Chapter 2 the (re)evolution into I4.0 is still ongoing. Therefore research gaps across all dimensions exist making it harder to gather consensus on how to achieve I4.0 upper levels. Concepts presented are still open to interpretations in most cases but with more applications and real world testing the rating concepts will be able to be better fine-tuned to become clearer and easier to follow.

Still regarding the assessment guide table it is believed to be beneficial to turn it into a mobile device application and enable it to be more interactive and intuitive. This would help to speed up analysis in real-time during the actual assessment and reduce time consumption.

For the implementation the proposed solution in the case study a universal model framework for a HMI was developed by a software team. After this concrete project is fully implemented a web application can be developed to further speed up HMI design. The purpose of such web application would be to serve as middleware between designers and programmers. A project design team would gather and feed into the web application the necessary inputs such as process variables, KPI and other relevant desired information for the customer. The web application would then convert and output this data directly into the HMI model framework. This will create an automated process of feeding a universal HMI model that frees up programmers from repetitive data entry allowing them more time to deal with other problematic implementation issues.

Bibliography

[1] H. Kagermann, W. Wahlster, and J. Helbig, “Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 Working Group,” *Final Rep. Ind. 4.0 WG*, no. April, p. 82, 2013.

[2] Y. Lu, “Industry 4.0: A survey on technologies, applications and open research issues,” *J. Ind. Inf. Integr.*, vol. 6, pp. 1–10, 2017.

[3] L. Monostori *et al.*, “Cyber-physical systems in manufacturing,” *CIRP Ann.*, vol. 65, no. 2, pp. 621–641, 2016.

[4] I. Castelo-Branco, F. Cruz-Jesus, and T. Oliveira, “Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union,” *Comput. Ind.*, vol. 107, pp. 22–32, 2019.

[5] Instituto Nacional de Estatistica - Portugal, “Inquérito às Práticas de Gestão,” 2018.

[6] S. Silva, “Economia portuguesa precisa de melhores pasteleiros,” *Público.pt - Especial Executivos*, 2019. [Online]. Available: https://www.publico.pt/2019/10/01/sociedade/noticia/economia-portuguesa-precisa-melhores-pasteleiros-1888332. [Accessed: 28-Oct-2019].

[7] P. Schneider, *Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field*, vol. 12, no. 3. Springer Berlin Heidelberg, 2018.

[8] M. Krugh and L. Mears, “A complementary Cyber-Human Systems framework for Industry 4.0 Cyber-Physical Systems,” *Manuf. Lett.*, vol. 15, pp. 89–92, 2018.

[9] OECD (2017), “The Next Production Revolution - Implications for Governments and Business,” 2017. [Online]. Available: https://www.oecd.org/innovation/the-next-production-revolution-9789264271036-en.htm. [Accessed: 18-Jun-2019].

[10] H. Kagermann, “Industrie 4 . 0 – What can the UK learn from Germany ’ s manufacturing strategy ?,” *Royal Academy of Engineering*, 2014. [Online]. Available: https://www.raeng.org.uk/RAE/media/Events/Programmes/20140204-industrie4-Henning-Kagermann.pdf.

[11] M. Hankel and B. Rexroth, “Status Report - The Reference Architectural Model Industrie 4.0 (RAMI4.0),” *Vdi/Vde,Zvei*, 2015. [Online]. Available: https://www.zvei.org/en/subjects/industrie-4-0/the-reference-architectural-model-rami-40-

and-the-industrie-40-component/.

[12] A. Rojko, "Industry 4.0 Concept: Background and Overview," *Int. J. Interact. Mob. Technol.*, vol. 11, no. 5, pp. 77–90, 2017.

[13] V. Alcácer and V. Cruz-Machado, "Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems," *Eng. Sci. Technol. an Int. J.*, vol. 22, no. 3, pp. 899–919, 2019.

[14] R. Y. Zhong, X. Xu, E. Klotz, and S. T. Newman, "Intelligent Manufacturing in the Context of Industry 4.0: A Review," *Engineering*, vol. 3, no. 5, pp. 616–630, 2017.

[15] T. K. Sung, "Industry 4.0: A Korea perspective," *Technol. Forecast. Soc. Change*, vol. 132, no. October 2017, pp. 40–45, 2018.

[16] S. Mittal, M. A. Khan, D. Romero, and T. Wuest, "A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)," *J. Manuf. Syst.*, vol. 49, no. June, pp. 194–214, 2018.

[17] R. A. Rojas, E. Rauch, R. Vidoni, and D. T. Matt, "Enabling Connectivity of Cyber-physical Production Systems: A Conceptual Framework," *Procedia Manuf.*, vol. 11, no. June, pp. 822–829, 2017.

[18] F. Ansari and U. Seidenberg, "A portfolio for optimal collaboration of human and cyber physical production systems in problem-solving," in *13th International Conference on Cognition and Exploratory Learning in Digital Age 2016*, 2016, pp. 311–314.

[19] M. P. Groover, "PART IV: Manufacturing Systems (Ch.13-19)," in *Automation, Production Systems, and Computer-Integrated Manufacturing*, 4th ed., Pearson, 2015, pp. 353–574.

[20] J. Qin, Y. Liu, and R. Grosvenor, "A Categorical Framework of Manufacturing for Industry 4.0 and beyond," *Procedia CIRP*, vol. 52, pp. 173–178, 2016.

[21] M. Bortolini, F. G. Galizia, and C. Mora, "Reconfigurable manufacturing systems: Literature review and research trend," *J. Manuf. Syst.*, vol. 49, no. July, pp. 93–106, 2018.

[22] J. A. Saucedo-Martínez, M. Pérez-Lara, J. A. Marmolejo-Saucedo, T. E. Salais-Fierro, and P. Vasant, "Industry 4.0 framework for management and operations: a review," *J. Ambient Intell. Humaniz. Comput.*, vol. 9, no. 3, pp. 789–801, 2018.

[23] E. A. Lee, "Cyber physical systems: Design challenges," *Proc. - 11th IEEE Symp. Object/Component/Service-Oriented Real-Time Distrib. Comput. ISORC 2008*, pp. 363–369, 2008.

[24] K. D. Thoben, S. A. Wiesner, and T. Wuest, "'Industrie 4.0' and smart manufacturing-a review of research issues and application examples," *Int. J. Autom. Technol.*, vol. 11, no. 1, pp. 4–16, 2017.

[25] C. Liu and P. Jiang, "A Cyber-physical System Architecture in Shop Floor for Intelligent Manufacturing," *Procedia CIRP*, vol. 56, pp. 372–377, 2016.

[26] P. Hehenberger, B. Vogel-Heuser, D. Bradley, B. Eynard, T. Tomiyama, and S. Achiche, “Design, modelling, simulation and integration of cyber physical systems: Methods and applications,” *Comput. Ind.*, vol. 82, pp. 273–289, 2016.

[27] J. Lee, B. Bagheri, and H. A. Kao, “A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems,” *Manuf. Lett.*, vol. 3, pp. 18–23, 2015.

[28] C. G. Rieger, D. I. Gertman, and M. A. McQueen, “Resilient control systems: Next generation design research,” *Proc. - 2009 2nd Conf. Hum. Syst. Interact. HSI ’09*, pp. 632–636, 2009.

[29] A. Sanders, C. Elangeswaran, and J. Wulfsberg, “Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing,” *J. Ind. Eng. Manag.*, vol. 9, no. 3, p. 811, 2016.

[30] R. Sharpe, K. van Lopik, A. Neal, P. Goodall, P. P. Conway, and A. A. West, “An industrial evaluation of an Industry 4.0 reference architecture demonstrating the need for the inclusion of security and human components,” *Comput. Ind.*, vol. 108, pp. 37–44, 2019.

[31] McKinsey, “Industry 4.0 - how to navigate digitization of the manufacturing sector,” *McKinsey Digit.*, pp. 1–62, 2015.

[32] D. Wee and C. Baur, “Manufacturing’ s next act,” *McKinsey & Company&Company*, no. JUNE, pp. 1–5, 2015.

[33] S. V. Buer, J. O. Strandhagen, and F. T. S. Chan, “The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda,” *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2924–2940, 2018.

[34] W. E. Deming, *The New Economics for Industry, Government, Education*, 3rd ed. MIT, 2018.

[35] J. K. Liker, *The Toyota way: 14 management principles from the world’s greatest manufacturer*. Mcgraw-Hill, 2004.

[36] T. Wagner, C. Herrmann, and S. Thiede, “Industry 4.0 Impacts on Lean Production Systems,” *Procedia CIRP*, vol. 63, pp. 125–131, 2017.

[37] J. Bicheno and M. Holweg, *The Lean Toolbox - The essential guide to Lean transformation*, 4th ed. PICSIE Books, 2009.

[38] A. Mayr *et al.*, “Lean 4.0-A conceptual conjunction of lean management and Industry 4.0,” *Procedia CIRP*, vol. 72, pp. 622–628, 2018.

[39] T. Wagner, C. Herrmann, and S. Thiede, “Identifying target oriented Industrie 4.0 potentials in lean automotive electronics value streams,” *Procedia CIRP*, vol. 72, pp. 1003–1008, 2018.

[40] Lean Enterprise Institute, *Lean Lexicon - a graphical glossary for Lean Thinkers*, 4th ed. The Lean Enterprise Institute, Inc, 2008.

[41] T. Ben Romdhane, A. Badreddine, and M. Sansa, “A new model to implement Six Sigma in small- and medium-sized enterprises,” *Int. J. Prod. Res.*, vol. 55, no. 15, pp. 4319–4340, 2017.

[42] B. Almannai, R. Greenough, and J. Kay, “A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies,” *Robot. Comput. Integr. Manuf.*, vol. 24, no. 4, pp. 501–507, 2008.

[43] L. H. Chen and C. N. Chen, “Normalisation models for prioritising design requirements for quality function deployment processes,” *Int. J. Prod. Res.*, vol. 52, no. 2, pp. 299–313, 2014.

[44] Robin E. McDermott, Raymond J. Mikulak, and Michael R. Beauregard, *The Basics of FMEA*, 2nd ed., vol. 2. 2009.

[45] A. Rastogi, “DMAIC – A Six Sigma Process Improvement Methodology | Quality Management - 7 Basic Quality tools,” *Grey Campus*, 2018. [Online]. Available: https://www.greycampus.com/blog/quality-management/dmaic-a-six-sigma-process-improvement-methodology. [Accessed: 04-Jul-2019].

[46] J. Delaram and O. Fatahi Valilai, “An architectural view to computer integrated manufacturing systems based on Axiomatic Design Theory,” *Comput. Ind.*, vol. 100, no. December 2017, pp. 96–114, 2018.

[47] M. G. Violante and E. Vezzetti, “Kano qualitative vs quantitative approaches: An assessment framework for products attributes analysis,” *Comput. Ind.*, vol. 86, pp. 15–25, 2017.

[48] K. (Wayne S. U. Yang and H. (Wayne S. U. Zhang, “A Comparison of Triz and Axiomatic Design,” 2000. [Online]. Available: https://triz-journal.com/a-comparison-of-triz-and-axiomatic-design/. [Accessed: 05-Jul-2019].

[49] SolidCreativity, “TRIZ Matrix online / 40 principles / TRIZ contradictions table,” 2014. [Online]. Available: http://www.triz40.com/TRIZ_GB.php. [Accessed: 05-Jul-2019].

[50] A. Cala *et al.*, “Migration from traditional towards cyber-physical production systems,” *Proc. - 2017 IEEE 15th Int. Conf. Ind. Informatics, INDIN 2017*, pp. 1147–1152, 2017.

[51] American Society for Quality, “Plan-Do-Check-Act (PDCA) Cycle,” 2019. [Online]. Available: https://asq.org/quality-resources/pdca-cycle. [Accessed: 04-Jul-2019].

[52] CreativeSafetySupply.com, “8D for Problem Solving,” 2017. [Online]. Available: https://www.creativesafetysupply.com/articles/8d-for-problem-solving/. [Accessed: 11-Sep-2019].

[53] ASQ.org, “What are the eight disciplines (8D)?,” 2013. [Online]. Available: http://asq.org/quality-progress/2012/12/back-to-basics/breaking-it-down.html. [Accessed: 11-Sep-2019].

[54] A. Ayulo, “Dissecting the problem-solving A3 report,” *ASQ.org - Quality Progress*, 2012. [Online]. Available: http://asq.org/quality-progress/2012/12/back-to-basics/breaking-it-down.html. [Accessed: 11-Sep-2019].

[55] T. Liesener, “PDCA, A3, DMAIC, 8D/PSP - what are the differences?,” 2013. [Online]. Available: https://kaizen-factory.com/2013/09/11/pdca-a3-dmaic-8dpsp-what-are-the-differences/. [Accessed: 11-Sep-2019].

[56] VDI, “VDI/VDE 3695: Engineering von Anlagen - Evaluieren und optimieren des Engineerings,” 2010. [Online]. Available: https://www.beuth.de/de/technische-regel/vdi-vde-3695-blatt-1/135465140.

[57] S. Biffl and H. Steininger, “Engineering Process Improvement based on VDI 3695,” 2016. [Online]. Available: http://cdl.ifs.tuwien.ac.at/files/sps2016_cdl_engprimpr_en.pdf. [Accessed: 04-Jul-2019].

[58] J. Gausemeier and S. Moehringer, “New guideline VDI 2206 - A Flexible Procedure Model for the Design of Mechatronic Systems,” *Int. Conf. Eng. Des.*, pp. 1–10, 2003.

[59] K. Grzybowska and A. Łupicka, “Key competencies for Industry 4.0,” *Econ. Manag. Innov.*, vol. 1, no. October, pp. 250–253, 2017.

[60] C. A. O’Reilly, J. Chatman, and D. F. Caldwell, “People and Organizational Culture: a Profile Comparison Approach To Assessing Person-Organization Fit,” *Acad. Manag. J.*, vol. 34, no. 3, pp. 487–516, 1991.

[61] F. Steiner, “Ramp-up management as an approach to mitigating instability in the adaptation of solution spaces in high-variety business environments,” *Procedia CIRP*, vol. 20, no. C, pp. 32–37, 2014.

[62] P. Leal, R. N. Madeira, and T. Romão, “Model-Driven Framework for Human Machine Interaction Design in Industry 4.0,” pp. 644–648, 2019.

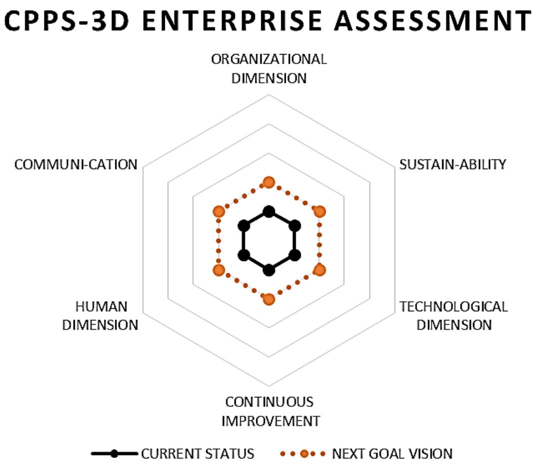
Appendix I.

Assessment guide table and ratings

This appendix presents the Excel template of the Assessment guide table and radar. It also presents the six tables relative to the rating concepts used to evaluate each different category, namely Organizational dimension, Sustainability, Technological dimension, Continuous improvement, Human dimension and Communication.

Appendix I.1. CPPS-3D Assessment guide table Template and Radar

(Enterprise Name) (Date)		CURRENT STATUS		NEXT GOAL VISION	
CPPS-3D		LEVEL	COMMENTS	LEVEL	OBJECTIVE
ORGANIZATIONAL DIMENSION	Organization in production and Support Functions	1		2	
	Customer focus and employee awareness	1		2	
	Workplace Organization and Visual Management	1		2	
SUSTAIN-ABILITY	Audit and Control Processes	1		2	
	Quality and Safety	1		2	
TECHNOLOGICAL DIMENSION	Standard Work	1		2	
	Reliability and Robustness	1		2	
	Processes and affective resources	1		2	
	Integration and automation	1		2	
CONTINUOUS IMPROVEMENT	Problem solving	1		2	
	Performance Improvement	1		2	
	Management of Improvement Ideas	1		2	
HUMAN DIMENSION	Versatility / Backup Capacity	1		2	
	Role of leadership	1		2	
COMMUNI-CATION	Performance evaluation	1		2	
	Communication for the management of operations	1		2	



Appendix I.2. CPPS-3D Organizational dimension level concepts

ORGANIZATIONAL DIMENSION	
Organization in production and Support Functions	1 - Machines linked to ERP
	2 - Individual machine performance indicators on shop floor in real-time
	3 - Real-time production system information available anywhere
	4 – Use of collaborative decision-making environment
	5 - Decentralized control system architecture
Customer focus and employee awareness	1 - No production data presented to customer, product is delivered to customer as ordered
	2 - Production data available to customer at location
	3 - Production status monitoring in real-time anywhere by customer
	4 - Collaborative product improvement projects environment
	5 - Joint cloud-based product design and development
Workplace Organization and Visual Management	1 – Implementation of 5S/zoning/Poka-yoke, physical local Andon board (status and disruption indicators)
	2 - Andon board remotely accessible
	3 – Automatic targeted notifications to users
	4 - Auto-ID and Augmented Reality to support 5S, zoning, Poka-yoke
	5 - Machine-learning algorithms for auto-adjust to irregularities

Appendix I.3. CPPS-3D Sustainability level concepts

SUSTAINABILITY	
Audit and Control processes	1 - KPI generation by ERP and available to top management
	2 - KPI information available at the shop floor
	3 - Targeted production information available remotely in real-time
	4 - Integrated simulation for production optimization
	5 – Computer algorithms to self-adjust production due to resources constraints and environment changes
Quality and Safety	1 - Standardized production processes. Manual inspection of parts. Personal protection equipment.
	2 - Automation for repeatability. Physical barriers to automated hazards.
	3 – Use of human-mistake minimizing technologies (e.g. Auto-ID parts, intelligent bins, AGV transport system)
	4 – Creation of collaborative human-robot workspaces
	5 – Full automated work environments. No routine tasks by humans. Self-routing AGV system.

Appendix I.4. CPPS-3D Technological dimension level concepts

TECHNOLOGICAL DIMENSION	
Standard Work	1 - No rotation of workers. Specific tasks executed by specific workers.
	2 – Documented standard work procedures. Section workers rotate functions.
	3 - Standard work procedures training across different production sections.
	4 – Assistance and guidance of tasks by Augmented Reality devices
	5 – Virtual Reality worker's training
Reliability and Robustness (stability against disturbances)	1 – ERP generated historical data analysed by management
	2 – Smart sensors that communicate faults and errors to a server, Machine health monitoring analytics
	3 – Production system monitoring, analytics for historical data of similar machines.
	4 - Integrated simulation for definition of preventive actions towards disturbances avoidance
	5 – Decentralized architecture (all information constantly replicated in the network so no single point of failure), self-adjust algorithms to disturbances
Processes and affective resources	1 - Functional focus by production sections
	2 – Resource sharing across sections, Common technological standards.
	3 – Multifunctional production equipment (e.g. adaptable robots, intelligent conveyor systems, Auto-ID parts, intelligent bins, AGV transport)
	4 – Integrated simulation for production optimization
	5 - Automated work environments. No routine tasks by humans
Integration and automation	1 – PLC controlled automation, Vertical integration by ERP
	2 – Wireless communications, Analytics for multi-dimensional data correlation
	3 – Horizontal integration of processes, central hub server for real-time remote data access
	4 – Digital twin model for integrated simulation of systems, Integration with suppliers and customers
	5 – Decentralized automation architecture

Appendix I.5. CPPS-3D Continuous improvement level concepts

CONTINUOUS IMPROVEMENT	
Problem solving	1 – ERP system to record data, Problems analysis by in-house process experts
	2 – Real-time production information available
	3 – Knowledge-sharing practices (transfer acquired knowledges from the workforce to the production system)
	4 – Big data analysis algorithms (data mining)
	5 – Machine learning, Predictive analytics algorithms
Performance improvement	1 – ERP data collection
	2 – Real-time production information available
	3 – Use of specific integrated management software (e.g. Manufacturing Execution System (MES), Supply Chain Management (SCM), etc.)
	4 – Increased workers capabilities through use of AR technology
	5 - Virtual Reality worker's training, decentralized automation architecture, self-adjust algorithms to disturbances
Management of improvement ideas	1 – Ideas shared through hierarchical structure
	2 – Promotion of open sharing and discussion of ideas
	3 – Internal web-based platform for gathering, sharing and evaluating ideas
	4 – Web-based platform for integration with partners, joint search for improvements
	5 – Inter-organizational joint database of ideas, Smart search algorithms

Appendix I.6. CPPS-3D Human dimension level concepts

HUMAN DIMENSION	
Versatility/ /Backup capacity	1 – No rotation of functions or only workers in the same production section can rotate functions.
	2 – Training across different production sections
	3 - Plug and play people (portable sensors for data collection), Analytics for human readiness monitoring, Recognition of variation/patterns over time
	4 - Assistance and guidance of tasks by Augmented Reality devices
	5 – Intelligent Augmented Reality (use of Artificial Intelligence algorithms to recognize user and adapt user experience (UX) in real-time)
Role of leadership	1 – Traditional top-down structure focused on delivering final product
	2 – Organizational dimension culture: Strategic migration plans established, Promotion of digital capabilities across the whole enterprise
	3 – Technological dimension culture: Promotion of experimentation, risk-taking and collaboration (e.g. new technological pilot projects)
	4 – Human dimension culture: Focus on supporting workers, Motivation by creating acceptance for change and counteracting organizational inertia
	5 – Data-driven leadership through integration with suppliers and customers

Appendix I.7. CPPS-3D Communication level concepts

COMMUNICATION	
Performance evaluation	1 – ERP production KPI analysis by top management, qualitative worker's evaluation by supervisors
	2 – Remotely available production system information in real-time
	3 – Use of specific integrated management software (e.g. Manufacturing Execution System (MES), Supply Chain Management (SCM), etc.)
	4 – Model-based analytics for better KPI definition
	5 - Integrated simulation for optimal metrics definition
Communication for the management of operations	1 – ERP data collection, Information flow through managerial hierarchy
	2 – Individual KPI indicators on shop floor
	3 – Remotely available production system information in real-time
	4 – Integration with suppliers and customers, Integrated simulation for decision-support
	5 – Predictive analytics algorithms for personalised information