Development of IoT solutions according to the PLM approach

Francesco Serio[1[0000-0001-7533-8581]], Ahmed Awouda[1[0000-0002-6079-0919]], Mansur Asranov[1,2[0000-0002-3144-9711]] and Paolo Chiabert[1 [0000-0002-4740-9896]]

[1] Politecnico di Torino - Corso Duca degli Abruzzi, 24, Torino (TO) 10129, Italy
[2] Turin Polytechnic University in Tashkent, Kichik Halqa Yuli 17, 100095 Tashkent

Abstract. The Industrial Internet of Things (IIoT) is one of the nine enabling technologies of Industry 4.0, which in recent years has seen an exponential increase in its applications. New production devices that are naturally equipped with this technology and the retrofitting solutions for industrial devices already installed in our industries, promote the demand of IIoT solutions. The Internet of Thing is often associated with Product Lifecycle Management (PLM) due to its ability to provide data which, when appropriately analyzed, feed the PLM system allowing for the tracking of the product along its life cycle.
In this paper, the point of view is reversed: the IIoT solution, which is designed, implemented and maintained in an industrial system, is the product that must be managed with a PLM approach.
IIoT solutions have characteristics that require the use of a PLM approach: they must meet complex requirements, they must adhere to standards and be compatible with the company's existing IT infrastructure, they are complex systems that interface many other systems and have a long lifecycle during which they are subject to innumerable modifications and extensions.
It is therefore justified, from a research point of view, to investigate the characteristics that a PLM approach must have to support the development of an IIoT solution.
This paper, based on the theory and evidences from industries and academies, traces a reference framework for the development of an IIoT solution supported by the PLM approach.
To test the validity of the proposed guidelines, the paper illustrates their application in the development of a simple IoT solution dedicated to teaching and training.

Keywords: Product Lifecycle Management Guidelines, Industrial Internet of Things solutions, Knowledge Management.

1 Introduction

Nowadays, insiders are well aware of both the nine technologies of Industry 4.0 (I4.0) and their relevance in renewing manufacturing strategies [1]. Among these nine, Internet of Things (IoT) has been considered a key technology due to its potential to be a game changer [2]. In addition, the most recent production devices that are naturally equipped with this technology and the retrofitting solutions for industrial machines already installed in our industries, promote the diffusion of Industrial Internet of Things (IIoT) solutions.

On the other hand, Product Lifecycle Management (PLM) is "a business strategy for creating and sustaining such a product-centric knowledge environment. It is rooted not only in design tools and data warehouse systems, but also on product maintenance, repair and dismissal support systems. A PLM environment enables collaboration between – and informed decision making by – various stakeholders of a product over its lifecycle" [3].

The IoT is often associated with PLM for its ability to provide data which, when properly analyzed, feed the PLM system allowing product traceability along its life cycle. In this paper, we change this prospective considering the IIoT solution as the final product to manage with a PLM approach because the scientific and technical literature does not show solid evidence of structured approach for developing IIoT solutions. For this purpose, we investigate the characteristics that a PLM approach must have to support the development of an IIoT solution taking into account its requirements, the standards to adhere with, the necessity to interface with the existing IT infrastructure and the need to update the IIoT solution during its lifecycle. An IIoT solution is not a single electronic product but a framework that includes hardware, software and infrastructural components. Differently from other electronic solutions, IIoT is inherently an open framework that dramatically changes along the time, where components are often upgraded with relevant new characteristics, in order to fulfil dynamic customer's demand or exploit technological innovation.

After this section, that introduces and contextualize the research work, you will find the literature review about IoT, IIoT, PLM and their interaction. Subsequently, we propose a reference framework for the development of an IIoT solution supported by the PLM approach and we test it on a simple IoT solution dedicated to teaching and training. Finally, the last section states the conclusions and the possible future works related to these topics.

2 Research context

2.1 IoT and IIoT

For some years now, the Internet of Things has begun to influence and change our lives and habits. IoT is composed of devices that have sensors to gather and communicate data through network protocols. The availability of huge amount of data, that can be crossed and analyzed, provides valuable information for customers and producers. In [4] and [5], the concepts are described in detail.

The declination of the IoT in the manufacturing industry is called the Industrial Internet of Things [6], where production machinery, conveyors, products, semi-finished products, raw materials and lately wearables worn by operators constantly send information about the production line or the entire plant in order to identify and correct errors promptly.

Furthermore, again thanks to IoT technologies, manufacturers can check the products leaving the factory to understand how and where they were distributed, consequently derive the demand rate in a given area and potentially eliminate out of stock and overproduction scenarios. Finally, thanks to some IoT technologies, such as RFID and barcodes, distributors can trace the arrival of products from the various manufacturers and manage warehouses, accounting and many other business areas.

2.2 PLM approach

Taking into account the maturity of this topic, PLM has been defined from many experts until now. Among the most important contributions are worth mentioning those of Michael Grieves [3], with its definition of PLM model and of Mirrored Spaces Model, the one by Saaksvuori and Immonen [7] and the one by John Stark [8], who introduced an approach to correctly implement PLM in a firm following a series of ten steps. According to Terzi et al. [9], PLM generally refers to three distinct periods of the life of any product (see figure 1): Beginning of Life (BOL), Middle of Life (MOL), and End of Life (EOL). Given the complexity of each of these phases, many papers in the literature focuses only on one of them. In addition, the BOL is certainly the most complicated one because it has its origins in the product development (PD) process consisting of several phases that are constantly increasing their complexity. However, although the product development process is different for each company and above all for each industry, it is usual to define some typical common phases. Examples are given by the models proposed by Pahl & Beitz' [10], Ulrich & Eppinger (U&E) [11] and by the ASME\ANSI standards [12]. This paper considers the PD process defined by U&E as reference model for its intuitiveness and because it effectively supports the didactic purpose. The U&E model consists of six phases (see Figure 2) that starting from many product concepts reduces the number of alternatives to the best one, which must pass all the different tests and must meet technical specifications and customer needs. The decision to go more into detail on the PD process is dictated by its significant impact on production and product monitoring and, consequently, on the cost of the final product.

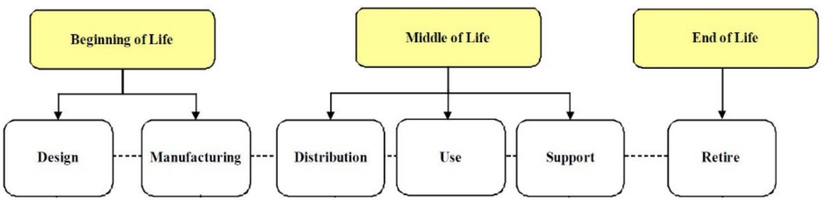

Fig. 1. Product Lifecycle periods [3]

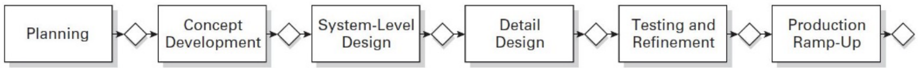

Fig. 2. The six phases of the generic development process [11]

2.3 IoT for PLM

In order to know the state of the art regarding the interaction between IoT and PLM it has been used as starting point the Systematic Literature Review (SLR) presented by Barrios et al. [13] and referred to November 2021. The research was then updated on both Scopus and Web of Science (WOS) searching for the same key words. The results were similar to those reported in [13], because none of the latest paper considers PLM and IoT at the same time, but generally, they refer more at one of the two. In addition, it clearly emerges in all of these cases as the prospective goes always from IoT to PLM, which translates in the focus of creating the best IoT solution to feed the PLM information system and not in using PLM to support the development of an IoT solution. As a logical implication, the absence of this perspective in theory reflects the situation in practice, where IIoT solutions are not developed with a structured approach because they rely on industrial best practices that are rarely shared to preserve the intellectual properties. The only noteworthy article is “Edge-Computing and Machine-Learning-Based Framework for Software Sensor Development” [14], where the authors propose a PLM approach to manage software sensors and in particular Machine Learning (ML) Algorithm. However, ML algorithms should be considered within another technology in I4.0 umbrella, which is Data Analytics rather than IoT solutions.
For these reasons, the focus of this manuscript is inverted compared to all the other papers because it proposes the creation of an IIoT solution with a PLM approach, where the IIoT solution is seen as a product itself.

2.4 Why PLM for IoT solution

The main reason why to use PLM is the complexity management declined in many areas such as product design, time to market (TTM), standards and rules, supply chain extension, geographical distribution of design and manufacturing centers, different and complex software with many hardware and software architecture available.

On the other hand, the product complexity is constantly increasing due to both the technological evolution of manufacturing processes and the number of components. The latter is especially true for some assembled products such as cars or electronics. For all these reasons is now common to refer to “smart products” as defined by Kristis [15]. Further parameter that increases the complexity are the time to store and retrieve information and, as said, the TTM reduction, i.e. the need to develop a product solution as fast as possible in order to anticipate all the competitors. For what concern the standards and rules to handle during the product lifecycle we can just cite some of them: Vision2000 [16], End of Life Vehicles Directive [17] and TREAD Act for the automotive industry [18], WEEE (EU Waste Electrical and Electronic Equipment) for the electronics industry [19] and the RoHS (Restriction of Hazardous Substances) in Electrical and Electronic Equipment Directive [20].

Given that IIoT and IoT solutions in general share these characteristics and problems, it was natural for us to think of these solutions as real products whose entire life cycle can be managed. Other reasons that motivate the usage of PLM in developing IIoT solution is the significant amount of failures in IoT projects, mainly related to obscured business aims, overlooked technological problems, unforeseen company organizational issues, and finally, customer and vendors misalignment [21]. In general, all these topics are properly managed when the project is driven by a PLM approach.

3 The proposed theoretical framework

The theoretical framework proposed in this chapter is based on PLM phases, defined by Terzi et al. [9], and depicted in Fig.1.

The BOL corresponds to the application of the U&E model to IIoT solutions development, which consists of the six phases illustrated in Fig. 2 and categorized into three main enterprise functions: marketing, design, and manufacturing. Table 1, structured starting from the U&E model, shows a general overview of the IIoT development framework for the BOL phase, the various functions involved in the different phases and how these functions are characterized in terms of core functions (Marketing, Design, Manufacturing, Other).

Table 1: Product Development Phases and Functions for developing an IoT product (BOL)

<table>
<tr><th></th><th>Planning</th><th>Concept Development</th><th>System-Level Design</th><th>Detail Design</th><th>Testing and Refinement</th></tr>
<tr><td rowspan="2">Marketing</td><td rowspan="2">Articulate market Opportunity
Industry 4.0 opportunity, Education & Professional Training Market Opportunity</td><td>Collect customer needs.
Needs in terms of Component functionality, scalability, network coverage, energy, open source</td><td rowspan="2">Develop plan for product options and extended product family
In case of different product variants develop taxonomy for product variation</td><td rowspan="2"></td><td rowspan="2">Facilitate Field testing
Prepare environment for testing HW, SW, Network, interface, cyber-security</td></tr>
<tr><td>Finance: Facilitate Economic analysis.
Compare various vendors, SW & HW options, Manufacturing, and assembly options</td></tr>
<tr><td>Design</td><td>Consider product platform and Architecture
Which IoT platforms & architectures, Software Options</td><td>Investigate feasibility of product concepts.
Software & Hardware compatibility, Structural feasibility</td><td>Develop product architecture.
Create SW & HW design, System architecture, structural design</td><td>Define items and interfaces
Complete structural design and CAD/CAE models</td><td>Test overall performance, reliability, and durability.
Test HW, SW, Network, interface, cyber-security</td></tr>
</table>

	Research & Find available technologies *Technologies related to: protocols, hardware and software, manufacturing methods*		Define major subsystems and interfaces & Preliminary component engineering. *Define HW, SW and structural subsystems and how they interact*	Define system and subsystem design. *Hardware design, Software and application design*	Implement design changes
Manufacturing	Identify production & assembly Constraints. *Physical constraints, software & hardware constraints*	Estimate Product & Manufacturing cost *BOM, cost breakdown for product components*	Identify suppliers for key components *Identify Platform, HW and SW vendors*	Define production processes. Define quality assurance processes	

The planning phase starts with the identification of opportunities, which is led by business strategy and includes an evaluation of market goals and technological advancements. The project mission statement, which details the product's target market, business objectives, major presumptions, and restrictions, is the result of the planning phase.

The target market's demands are determined during the concept development phase, and one or more concepts are chosen for further development and testing after being developed and evaluated. The form, purpose, and features of a product are described in a concept, which is typically supported by a set of requirements, a comparison to similar items, and an economic justification for the project.

In the system-level design phase, the product architecture is defined, the product is broken down into subsystems and components, essential components are provisionally designed, and responsibility for the detail designs is distributed among internal and external resources. During this stage, initial designs for the manufacturing system and final assembly are often developed as well. The output of this phase includes functional design specifications for each subsystem and should include architectures and geometric layout. The comprehensive definition of the structure, components, and properties of all the distinctive sections of the product as well as the identification of standard parts provided by suppliers, completes the detail design process. Each item has a process plan and control documentation, consisting of several files, which completely define the item, its interfaces with the system and its manufacturing or acquisition process.

The testing and refinement phase involves the construction and assessment of several preproduction versions of the product. The final phase is the production ramp-up phase where the product is made using the intended production system. Since these final phases have been partially applied in the case study the authors will not dive into details.

The MOL is based on three steps to be followed by the IIot solution users, comprehending the parts depicted in Figure 3, which shows the activities dependency. According to the figure 3, the Theoretical part is focused on developing and assessing fundamental knowledge and skills, the Practical part supports hands-on experience and finally the survey part collects necessary feedback from both the previous parts to improve the product. Notably, since the IIoT solution is one-of-a-kind product, in the authors approach the distribution phase is not considered.

The EOL, finally, takes into account all the actions needed to efficiently reuse all the IIoT solution components, in this case there will be two possible scenarios: 1) all the components are obsolete for their re-usage; 2) just some of the components are reusable. In the first scenario of the EOL, the solution will be donated as it is to a school for minor didactical activities. In the second scenario the reusable components will be employed to build the future prototype of the updated solution, instead the obsolete parts will be employed to manufacture a simpler solution to donate at the same target of the first scenario.

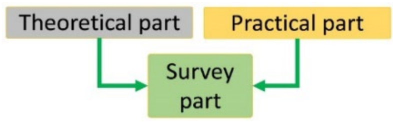

Fig. 3. PLM approach for a IoT solution (MOL)

4 Development of an IoT solution with a PLM approach

The need to mitigate common problems in implementing IoT solutions [21] stimulated authors to investigate the adoption of the proposed PLM approach in developing an IoT solution and testing its applicability with a didactic experiment. The latter highlighted the teaching and training activities aimed for reskilling IoT developers/designers. Main activities related to the development were organized according to the six phases of the U&E model included in the Beginning of Life period, as depicted in Figure 1 and 2.

4.1 Product design

The U&E model phases were customized for developing an IoT solution and performed according to the PLM approach. Each phase has been supported by the corresponding module available in PLM framework.

Planning. The aim of this phase is to conceive the concept mission statement through the opportunities identification. The objective of IoT solution is the development of a sandbox system, which could give the opportunity for data generation and acquisition, process monitoring and control. The solution should meet the following requirements: 1) components should be commercial and widely available, 2) allow for low-cost craftsmen manufacturing, 3) based on open-source solutions, 4) fast response to change, 5) minimal maintenance.

Concept Development. The planning of the IoT solution starts considering the main objective of the didactic activities: the interaction with sensors/actuators represents the customer needs, and professor guidelines for teaching activities defines the technical requirements. The concept of the system should meet the following categories of requirements: 1) device level requirements: installation of the sensors/actuators for data collection and device control should be simple for future replication. Moreover, variables from the devices should be simple and understandable, and reading/controlling should be easily performed; 2) Openness: hardware and software should be independent from vendor with wide integration opportunities; 3) Simplicity: software components should be simple to configure, deploy and verify, according to the Low-Code/No-Code Approach; 4) Scalability: The IoT solution should be scalable and portable.

System-Level design. The concept requirements impose specific challenges in terms of system-level design. The Figure 4 depicts System-level design of IoT solution, which consists of the following sub-systems: 1) structure/body – structural enclosure, which supports all other sub-systems; 2) Thermal and environmental subsystem – The components that generate thermal and environmental scenarios; 3) Sensors and actuators – various sensors for measuring variables, describing and monitoring thermal and environmental scenarios and actuators for controlling thermal and environmental sub-system components; 4) Logical subsystem – the components for data processing, actuators management, and users' interaction.

Leftstream arrows in Figure 4 represent datasets of the physical and dynamical variables, while rightstream arrows represent control information, which enforces changes in the thermal and environmental subsystem.

Fig. 4. System-Level Design of IoT solution

Detail design. Based on system level design, the detailed design process was broken down to the following engineering activities, performed by different design teams and operated according to Concurrent Engineering paradigm supported by PLM software:

1. Structural design – The objective of this project activity is to design the physical structure of the IoT solution, consisting of a modular polystyrene box, through the utilization of a CAD software. Deliverables of this activity are product data of the structure/body design, such as 2D drawings, 3D models, materials description, rendering, assembling instruction and simulation, cost analysis, etc. . Several modifications occurred with respect to the initial design requirements due to some criticalities related to the assembly phase and to the usability of the devices. The IoT sandbox consists of two environments separated by interchangeable solid or holed walls to allow different degrees of interaction. The covers of these two environments can be independently opened for maintenance and upgrading activities. Moreover, considerations on the integration of IoT components and constraints imposed by other teams, according to the flowchart in Figure 5, influenced the final design.
2. Thermal and environmental design – This activity designed the components for thermal and environmental scenarios, along with the required power supply. Two Peltier

cells were used to cool and heat the air inside the two chambers of the IoT sandbox for temperature and humidity variation. Three sets of lights were included to create lightning variation. Additionally, a thermodynamic model, also used for enabling a Cyber-Physical System, was developed to describe the heat exchange inside the chambers of the IoT sandbox. The outputs of this activity consist of Peltier cells and lights connection, power supply schemes and thermodynamic model description.

3. Sensors subsystem design – This activity developed sensors network for measuring the variation of humidity, lightning, current, voltage, and temperature inside the chambers, as well as outside of the IoT sandbox. Correspondingly, the sensors network design includes the sensors for temperature, humidity, light intensity, current and voltage. Additionally, several relays were added to the system for controlling Peltier cells and lights, thus, generating a complex interaction between the teams for thermal and sensors subsystems design. Output of this activity are the sensors and relays connection schemes.
4. Software and Control subsystem - The activity developed the IT system for collecting and managing the data obtained from the sensors network and for defining the control of thermal and light actuators. Raspberry Pi microcomputers were included in the design to handle computing workloads related to data processing, visualization, and control. Software part of the subsystem consists of MQTT broker service, which supports data transmission, and NodeRed responsible for data processing, visualization, and control logic. This bundle of software was containerized using Docker system to ensure portability and scalability. This activity generated important product data for the IoT solution, such as Raspberry Pi, sensors network and relays connection scheme, as well as NodeRed flows and MQTT broker configuration information. According to the PLM approach the product data generated in this activity must be stored, shared and upgraded according to the evolution of the IoT solution.

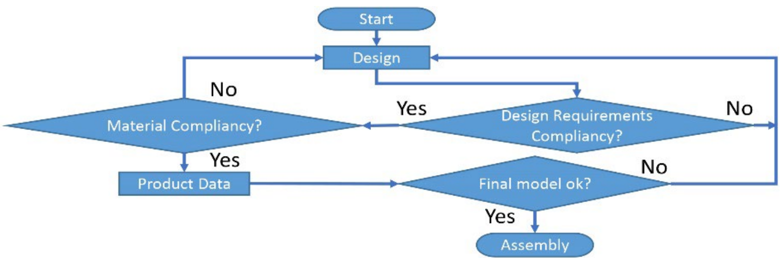

Fig. 5. Structural design methodology flowchart.

Testing and refinement. To ensure usability, reliability and durability of the IoT solution, two set of testing procedures of subsystems and functions were performed. The first was an inter subsystem test (integration between different subsystems) where signal and information exchange between subsystems, logical functionality of the software and cybersecurity resilience were tested. The latter was an intra subsystem test where each subsystem was tested individually against designed features and functionalities.

4.2 The IoT solution created

The product developed, is the Smart IoT box, a device with sensors and actuators that allows for data acquisition, processes monitoring and control. The device gives the opportunity to improve learning process and develop fundamental skills of building and managing IoT/IIoT solutions, one of the enablers for Industry 4.0 Paradigm.

Since the IoT solution is one-of-a-kind product, no comprehensive production planning is required. Furthermore, during the design process, several physical experiments (see Figure 6) have been carried out to verify critical aspects IoT solutions and provide the final proposed solution

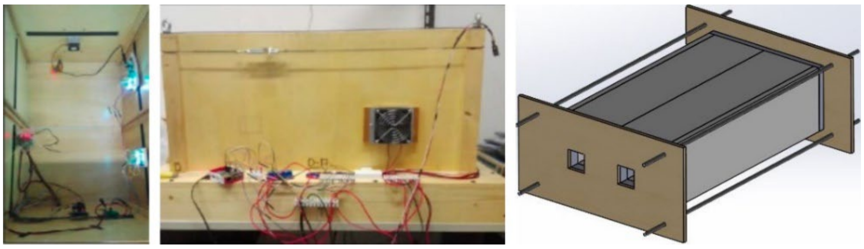

Fig. 6. Preliminary prototype of IoT sand box (left) e final proposal (right)

Taking into account the MOL, the Smart IoT box is intended to be used during practical activities in several courses offered for bachelor, master and PhD levels in field of Industry 4.0. Instead, during the EOL stage of the product lifecycle, the device is planned to be used as showcase for explaining disposal and recycling processes for HW and SW components of IoT products.

5 Conclusions

The paper analyzes the complexity of IIoT solutions and proposes a theoretical framework to manage their lifecycle with a PLM approach. Moreover, it reports a partial practical application of the proposed framework involving the Beginning Of Life based on the Ulrich & Eppinger model. The focus on the BOL period is justified by the relevance of the preliminary design decisions on overall costs, upgradability and scalability of the IIoT solution. However, the Middle Of Life and the End Of Life are not reported in the practical application because the MOL of our solution will start in the next didactic period.

The development of an IoT solution for didactic activities, to be performed in a didactic environment, demonstrates the applicability of the proposed approach and produces an effective One-of-Kind product. Nevertheless, open questions arise from the Middle of Life period where maintenance, upgrading and scalability are strictly required. Finally, open issues affect the End of Life period because it is not clear the role that HW and SW components will play into the Circular Economy model. Further investigations will address the open questions and issues that will be firstly verified in practice and secondly reported in future works.

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