Industry 4.0 Impact on Evolution of Product Development: The Bicycle Saddle Case Study

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***Abstract*—The emerging new technologies, the rapid change of market demand, and the influence of society moved the companies to be innovative and to improve their product as continuously as effectively. Therefore, the need for smart manufacturing systems and smart products arises to allow the manufacturer satisfying current customer needs, within a context of highly competitive market. The Industry 4.0 initiative provides a base toward the smart manufacturing, aimed at producing the smart and highly connected product. This study analyzes the role of Industry 4.0 technologies in the product development process. Particularly, it investigates how the whole life cycle of product is conceived, to comply with the Industry 4.0 main features. The paper focuses upon a customized bike saddle, assumed as a case study. The saddle comfort depends on many factors, including the rider anatomy. Therefore, it raises the necessity of profound customization to satisfy the user needs. Artificial intelligence techniques, such as data mining for market research, deep learning for customized design, and additive manufacturing technologies, as the stereolithography for 3D printing, concur all to enable the implementation of the Industry 4.0 paradigm, and to innovate significantly the product.**

Keywords—Industry 4.0, Product life cycle development, Customer needs, Smart product, Artificial intelligence, Data mining, Additive manufacturing, Systems Engineering.

I. Introduction

The fourth industrial revolution is transforming the society at least since the last decade [1]. The principal goal of that so-called strategic initiative is improving the value chain along the product life cycle development [2]. It resorts to some new technologies, enabling the revolution, as those related to Cyber-Physical Systems (CPS), looking as ones of the most important. They exploit a combination of physical and cybernetic systems [3]. As a result, decision-making is decentralized, through the process steps, and thus CPS lead to more stability and greater flexibility in system operation. The related technologies help the design, development, production, and delivery processes of an industrial product and of provided services, in different sectors, simultaneously and interactively [4].

As Klingenberg [4] mentioned, "The innovation rhythm and globalization create a hypercompetition business environment. It means shorter life cycles for products and services, which require flexibility and agility". It is known that Industry 4.0 can satisfy these requirements, when conceived systems are as modular and self-configurating or adaptable as possible. These features allow systems covering the niche market, where products are customized, at lower cost [4]. Wireless communication introduced the holistic access to the internet, for establishing an effective collaboration between humans and machines, within companies and even more in society [5]. Lasi et al. [6] and Kagermann [7] stated that the interconnection of objects and people, as well as merging physical and virtual worlds, led to a new type of information transparency. Here, the virtual world is a realistic copy of the physical world created [8], when linking sensor data with digitalized firm models, even by means of the so-called digital twin [9]. Its information can be like electronic documents, drawings, and simulation models. Crucial issues in this approach are the digitalization of the whole product life cycle management [10] and the integration between qualitative and quantitative design activities, exploiting a heterogeneous design environment, where functional and physical modeling operations meet and merge together [11]. Moreover, a new kind of smartness promotes the simultaneous adaptability of systems to the operating conditions and an effective and remote connection to other systems, for monitoring, communication and diagnosis purposes. This leads to the neologism "smart-nec-ness" [12], to represent objects, being simultaneously smart and highly connected [13].

II. Goals and Motivation

The combination of Artificial Intelligence (AI) and CPS has increased the level of autonomy in several production areas. It plays a vital role in transforming machines into more effective assistants for humans [14]. All the new features arisen with the fourth industrial revolution have reduced the impact of companies' obstacles to satisfy the market demand. Mass customization, change control management, complexity of the new products, cost, and time to market are typical examples of challenges, which the companies are struggling with [15].

In the specific context of test case, emerging cyclists' demand of performance, comfort and up-to-date bicycles requires an effective product customization. Comfort requires adequate sizing, suitable materials and practical assemblies of product, being result of the integration of fully compatible components. The bike saddle is a key part of the system, since more than several other ones is customized in size, material, design properties and functions. Designing a fit-to-purpose configuration of bicycle saddle needs to identify the main use of bike, for either professional activity or amusement. Moreover, a set of customer needs can be identified, by retrieving information from market, even by means of the AI techniques. Particularly, they allow analyzing the client review comments on online shopping websites, such as Amazon, instead of performing some direct surveys.

The commercial saddles for city, road, and mountain bikes usually fulfil requirements, which allow having a compromise among functionality, comfort, and cost for batch production. A customized configuration requires reaching a balance among those targets, even in case of a production limited to few samples. In this case, exploiting the enabling technologies of Industry 4.0 to reduce cost of each sample is mandatory.

This paper deploys the rationale applied to test case to merge the methodology of systems engineering and the approaches of Industry 4.0. It introduces two main parts. In the first one, an overview defines the relations between Reference Architecture Model for Industry 4.0 (RAMI 4.0) [16] and MBSE, as well as the real targets of smartness applied. The second one shows the application to test case. The contiguity between lean/smart manufacturing and the product lifecycle development is analyzed. A second section deals specifically with the smart connected product. Finally, the key enabling technologies of Industry 4.0 are applied to the definition of a roadmap, to develop an innovative configuration of customized bike saddle.

III. Product Lifecycle Development and Management

More than for other industrial products, the development of a new bicycle starts from a deep investigation of the customer needs [17]. A relevant part of the real appreciation of product depends on both subjective and objective feeling and perceptions of users. According to Systems Engineering, the requirement analysis is strongly basing on the identification of customer needs. The bicycle is a highly ergonomic product, i.e. the users interact with the system largely and by their body, with augmented exigencies in terms of aesthetics, in case of use for amusement, of performance, in case of professional use, and of high comfort in both of above mentioned user cases. Provided that main activities of product life cycle management [18, 19] consist of the requirement analysis and the definition of customer needs, and then of the product design, manufacture and delivery for service, the role of marketing and service monitoring is very important and strongly affects the product development.

A first step of investigation includes the collection of client views through the marketing, which can describe features and properties of the desired product [18], being often termed as product brief or design brief [19]. There are no official guidelines, even in this technical domain, for systematically identifying customer needs, although some experts show their personal skills in circumstantiating some appropriate needs, from preliminary data, by following a given driveline and in implementing their own systematic approach.

Five primary sources for driving needs, based on priority, are [18, 19]:

1) the customer expectation, detected through some direct interview or survey, or by reporting and feedbacks, from independent entities and warranty claims, etc.;
2) the innovation targets, or product features, making the product newer and innovative;
3) the constraints applied by the technical domain, in terms of available technologies and facilities of the manufacturer;
4) the industrial sources, such as trade journals and websites or suppliers' and competitors' catalogues;
5) the technical standards applied to the designed product and to its components.

As is known, customer needs turn out into some requirements, which must be specific, measurable, achievable, relevant and traceable. They usually are classified into functional, operational and architectural requirements. So far, precisely identifying and classifying the customer needs are mandatory. The Quality Function Deployment (QFD) is one of the most common techniques applied in this process of transforming the customer feeling into some circumstantiated product requirements. Despite its large use, the QFD sometimes does not support completely the action of prioritizing requirements, through some precise technical features [19]. Besides, mass customization, change control management, complexity of the new product, cost, and time to market are challenges for the companies following the conventional approaches for product development.

Those targets motivate the use of the Reference Architecture Model for Industry 4.0 (RAMI 4.0) [16]. RAMI 4.0 is a reference framework. It can be combined with those of the MBSE [20], and it defines a three-dimensional structure of the product life and value stream, hierarchy levels, and layers. Life and value stream dimension are suitable to measure the digitalization in product lifecycle development, as well as the vertical integration process [2, 21]. According to Bitkom [21], the product life cycle includes two stages: type and instance, as shown in Fig.1.

Fig. 1. Product life cycle as is modelled in the RAMI 4.0 framework [21].

The type stage includes concept design, product realization and prototype testing. As the production of each type of product starts and is prepared for sale, the next stage will begin. The instance stage refers to product manufacturing and usage by the customer. As the product is manufactured in series, and the MBSE becomes MPLE, i.e. the Systems Engineering applied a product line [22], any feedbacks about instance will reach directly to the manufacturer, to improve specifications and modify technical constraints for the design of the new type or product version. This approach is effective as large as the information from service are collected and driven back to the manufacturer. Consequently, the need for smartness arises. This turns out into a need for an effective cross-linking between different functional areas and steps of value stream, and for smart and highly connected products.

IV. Characterization of Product Smartness

The key features of the fourth industrial revolution consist, in the test case, in designing new smart products able to determine their state, to communicate to each other and to interact dynamically with operators. Connected objects are then organized and embedded into a reliable network, to compose a system of systems. The required smartness corresponds to the capability of collecting, storing, and communicating data and information, during the entire lifecycle [23]. The information may include genetic and intelligence data, respectively. The genetic data describe the product geometry, materials, and details of production. They are stored inside the component, are constant in time and usually unchangeable. The intelligence data give a feedback of product service, as, for instance, about mechanical and thermal loads applied, during both the production and the lifecycle. These data acquisitions need to resort to some sensors, exhibiting the technical ability to autonomously and inherently store and analyze the information. Retrieving from product those kinds of data allows improving the manufacturing process, especially for next generations of the same product, but even for the system maintenance, in service. In addition, real data recorded in manufacturing and in service allow refining the system models and making numerical simulations more precise [24].

In the context of Industry 4.0, this kind of smartness goes beyond the product. Each asset, including products, but also machines, production modules, systems, software, intellectual property, and humans represent itself as an entity. The asset becomes a crucial element as [25] "physical or logical object owned by or under the custodial duties of an organization, having either a perceived or an actual value to the organization". Particularly, the Asset Administration Shell (AAS) is used as a standardized tool (Fig.2). In practice, when the MBSE clearly defines the system through the Requirements Diagram (goals), the User Case Diagram (behavior), and the Block Definition Diagrams (architecture), the RAMI 4.0 can resort to the AAS to synthesize dependencies and properties of each element, seen as a part of the whole system.

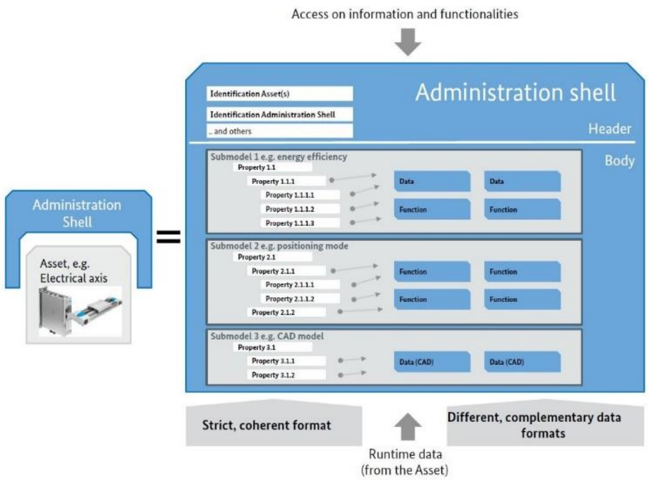

Fig. 2. General structure of asset and its administration shell [25].

V. USE OF THE KEY ENABLING TECHNOLOGIES OF INDUSTRY 4.0

The whole initiative Industry 4.0 promotes a conscious use of the new digital and industrial technologies. They exploit the very high level of connectivity between objects to embed some crucial capabilities of autonomous decision-making. A specific and current demand of customers concern the product quality as well as the design of individualized systems, making challenging the implementation of a flexible manufacturing (mass customization). Very often in the single item or small-lot production, the unstructured practical knowledge drives design and production. Besides that, the real-time data analysis and process monitoring can support the identification of an optimal solution for given product [24]. The new enabling technologies allow overcoming some challenging issues in that process. They provide interconnection, information transparency, decentralized decision-making and technical assistance [26], through the digitalization. Virtual engineering can now resort to digitalization to process a huge amount of real data, collected in operation by systems, to support both the functional and physical modeling activities, within the frame of heterogeneous simulation. The ideal process represented by the W-diagram [27], more than by the well-known V-diagram, is currently and more easily implemented. Particularly, as design and manufacturing issues are connected in the opposite branches of V-diagram, operation and diagnosis/maintenance are linked, in a second V, belonging two opposite branches. The RAMI framework drives to link the diagnosis, prognosis and monitoring with the design activity, since the beginning of the product lifecycle development.

For those purposes, the internet of things (IoT) and the cyber-physical systems are fundamental tools. They require efficiency in data mining, communication, cloud computing, and data analysis. The artificial intelligence facilitates the data elaboration to find a synthesis, helpful to improve the product quality and the efficiency of manufacturing. The designer fully exploits the digital twin and the augmented reality, for more accurate simulations, and thus reduces cost, faults in production, and time to market. Moreover, where the robots assist humans and improve productivity in the production line, the quality is increased. The modularization, with vertical and horizontal integration alongside Additive Manufacturing (AM) support the mass customization. A crucial issue is the cybersecurity in each layer of Industry 4.0 structure, to be carefully taken into account. According to that interpretation, all the digital technologies may play a significant role in the product innovation (Fig.3). The level of priority among those changes, product by product. In the test case, part of those have a stronger impact.

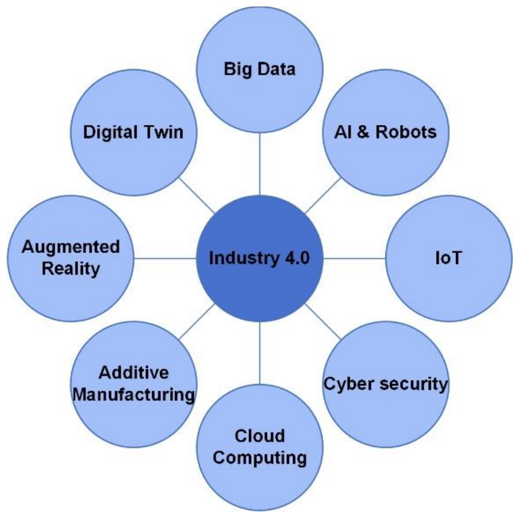

Fig. 3. Key enabling digital technologies in industry 4.0.

VI. THE CASE STUDY: THE BIKE SADDLE

The case study herein proposed deals with the bike saddle. The rider evaluates as a priority the saddle comfort. This is a property extremely subjective, but much more, it depends very deeply on even small details, as in fitted position on the bike, most riders claim some comfortability issues, in the saddle. It is known that the origin of pain comes from the touchpoints of the body, especially where bones interact with the saddle's shell, through the skin (Fig.4). Depending on the body structure and flexibility, and the variable cycling situations, each cyclist may feel different from another seating on the same saddle [28]. Therefore, it arises the need for customization in the saddle design and small-lot production.

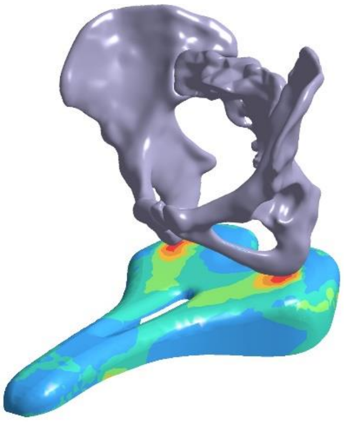

Fig. 4. The position of seat bones over the bike saddle and the pressure map on the bike saddle.

To make adaptable the saddle, it is possible measuring the pressure distribution over the saddle, using some pressure sensors [29]. They can identify the most stressed points of saddle, the pressure local maxima, where the contact interaction between user and saddle occurs. Moreover, in some road-cycling saddles, the break in the rail, which mounts the saddle to the bike body, is even a risk for safety [30].

Considering now the bike saddle as a product in the Industry 4.0 context, a process of customization to make more flexible the product design can start. The RAMI 4.0 proposes a suitable framework of product development. Therefore, one can define a suitable roadmap even for the bike saddle, as in Fig.5. It drives the designer to improve the product smartness, step by step, by considering in particular the instance stage of product development.

A. *Identification of customer needs*

As Fig.5 shows, the product development begins by collecting the customers' feedback, about current products from the active online shopping websites. This action allows detecting any weaknesses and even real strengths of products available on the market. This approach allows investigating the customer feeling, at lower cost, with a lower impact than in case of a direct interview, and thus the pros and cons of product could be better identified. Practically, the customer is invited to provide a review, with comments on the Amazon website, for the bike and a specific section deals with the saddle. The collection of reviews populates a database, to be exploited for a deeper analysis, in next steps. Some AI algorithms, such as those based on the neural networks may help the elaboration. Moreover, the designer can exploit even the Natural Language Processing (NLP), and the reinforcement-learning to analyze the data generated from business websites and social networks. The IBM Watson® and Google DeepMind® are examples of cognitive AI systems, that use those capabilities for data mining purposes [31, 32]. This study uses the data mining with NLP applied to the reviews database. The aim is doing a feature-based analysis for the product. The elicitation of customer preferences is included, as through the algorithm described in Fig.6.

This is a first example of application of the AI techniques to smart product design. The outcomes describe the most typical opinions of the customers, about specific features of the saddle product (Fig.7). These inputs are then exploited for the design concept and synthesis, respectively, as well as for the following verification and validation process [33].

In Fig.6, the structure of the feature-based analysis is drawn. Firstly, it is needed to normalize data in the database to be prepared for implementing NLP. This is the pre-processing. The extraction of product features is performed, by identifying frequent nouns, then pruning them, and finally mapping them to the potential features of the bike saddle. The sentiment analysis detects how the customer feels about some related features. The algorithms developed in the Python language for NLP allow elaborating those items. The polarity analysis applied to review sentences is then performed, by means of the Python Textblob® library. This tool quotes the writer attitude and emotion (negative, neutral, and positive) in the range −1 to 1. Those activities define the feeling state of the customer. Particularly, the polarity number in case of a comment representative of a worst emotion (e.g. -0.9) is lower (greater in absolute value but negative) than for a bad emotion (e.g. -0.3).

When the so-called sentiment analysis applies to each review sentence, including a specific product feature, it measures the customer satisfaction. To elaborate the whole investigation, the average polarity of all the review sentences is plotted vs. the feature polarity, as in Fig.7.

In this example, the polarity values show that the customer feeling about the saddle is good, since all the values are positive. Nevertheless, values are different for given feature. To gain a more positive feedback, the manufacturer should care about those, which exhibit a lower result, i.e. in Fig.7, the saddle shell and color. The analysis of some reviews suggests the common opinion of the customers about the saddle shell is that product comfortability is good. As Fig.7 shows, the cognitive AI methods overcome some typical inefficiencies of conventional approaches, in prioritizing requirements and technical features, as in the QFD process [31].

B. *Design concept and synthesis*

The design process considers simultaneously two bike versions, one for general customers, aimed at amusing people in bike operation, and a second for professionals, looking for performance. The customer needs previously identified help the designer to modify the current design of the bike saddle and to introduce a new concept design.

To make smart the saddle and retrieving information from operation, a new design includes a pressure sensor. It covers the bike saddle and measures the pressure applied by the user body, in terms of amplitude and distribution (Fig. 4). It is worth noticing that measurement can be continuous in time, to compare the pressure distribution in different cycling situations. Pressure changes during a race, for instance. It depends on the feeling of user, health and breathing conditions, road inclination and state, and even on time, when related to the fatigue suffered by the biker, being different at the beginning and at the end of race.

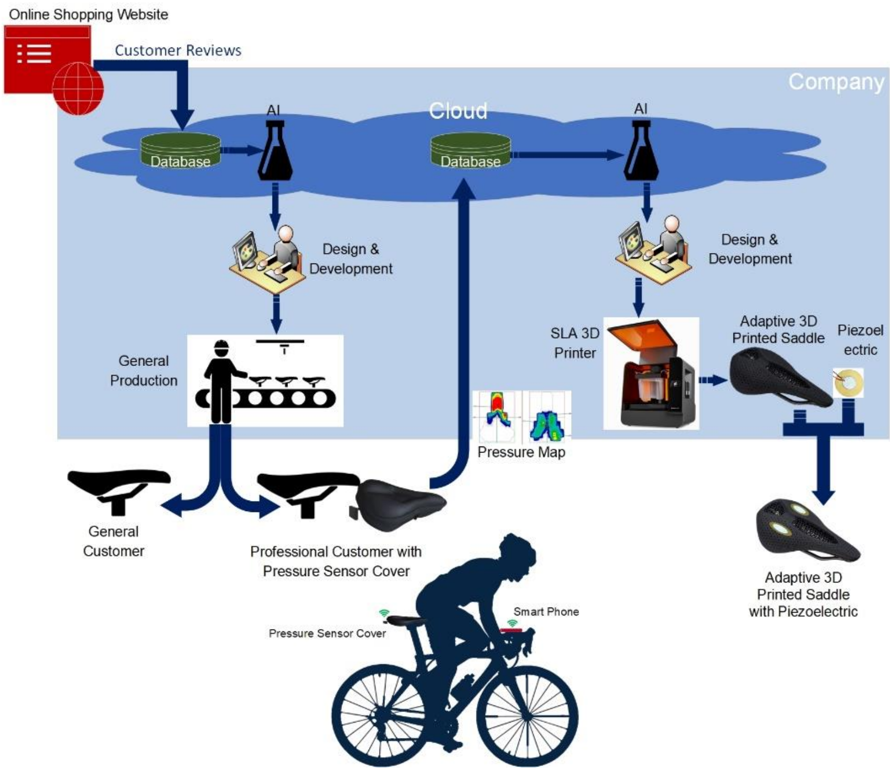

Fig. 5. Roadmap for the innovation of the bike saddle.

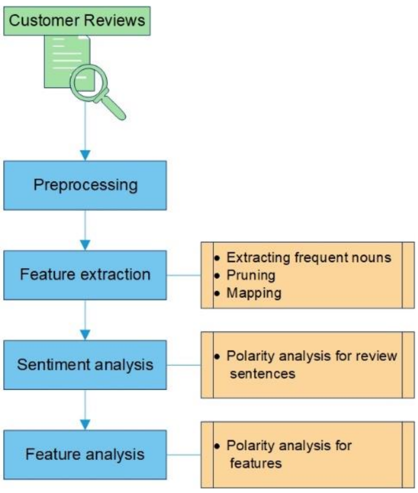

Fig. 6. The algorithm of the feature-based analysis.

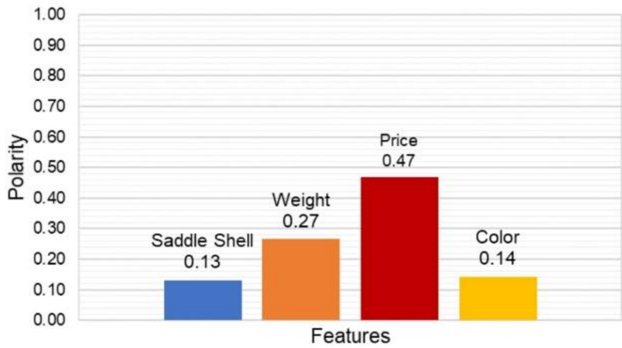

Fig. 7. Feature analysis of bike saddle.

The information related to pressure can be exploited to detect the state of biker, as well as the correct use of bike or any technical issues in its configuration, eventually even induced by materials wear and damage. The performance is increased by correlating the ergonomy of saddle and the postural configuration of biker in cycling. The selected pressure sensor is associated to a small communication system. The pressure data can be transmitted to a smartphone, in real-time, and through a wireless transmission system to an elaborating remote unit [34]. The smartphone (or any other smart device expressively located on the bike) uses an appropriate application to transmit the measured data to the cloud. The company (service or manufacturer) stores them, to create a database, associated with each cyclist. Some new techniques, such as the deep learning help the analyst to interpret results, to optimize the saddle layout for desired pressure distribution [35].

C. *Smart manufacturing*

As in several other cases, to produce a customized product, the high flexibility of manufacturing system is required, to realize a prototype quickly and with a suitable level of quality. In test case, the saddle must be produced in a small lot size. A compromise between the setting up of manufacturing system and the cost per unit must be found. The AM processes are good candidate to enable this customization. They exploit the Computer Aided Design (CAD) to adapt the prototyping in a short time [36, 37].

Among the AM technologies, and considering the materials (polymers) usually applied to produce a saddle, the Photopolymerization process is the best candidate. It consists in a stereolithographic process (SLA), encompassing the curing of a photosensitive monomer resin using a scanning laser or Ultra Violet (UV) radiation and transferring photoresin fluid into a crosslinked solid, as is illustrated in Fig.8 [38].

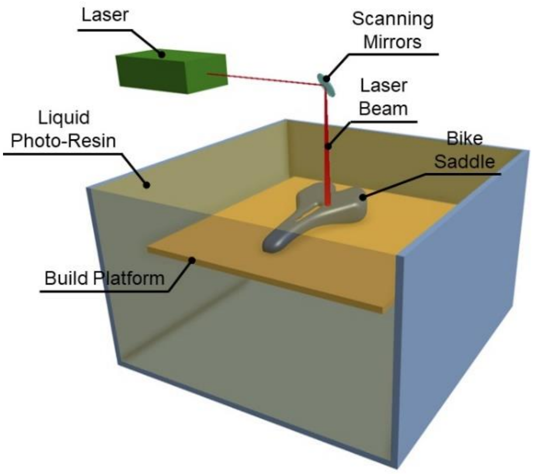

Fig. 8. Sketch of stereo-lithographic (SLA) process.

The SLA performs the fabrication of very detailed parts, with dimensions ranging from the micrometer to meter scale. It is current used for broad applications, such as dental models, hearing aids, fast prototyping, and tooling. Consequently, an SLA 3D printer can build the intended customized saddle [39, 40].

As an additional option, it is possible to place some piezoelectric layers in the saddle shell. The electromechanical coupling induced by the piezoelectric effect allows converting the mechanical stress into an electric charge, which is exploited, for either sensing [41] or storing energy [42]. The piezoelectric layers can provide the electric current feeding, for charging an embedded battery. This storage may supply energy to some electric consumers on board, as the Light-Emitting Diodes (LEDs), small sensors, data storage and communication devices.

The mechanical design of the saddle can be even improved, by resorting to some new technologies, selected among those declared as enabling the industrial revolution. To reach the best damping effect of the saddle, for instance, and to obtain a suitable amount of stress acting on the piezoelectric layers, the saddle material can include the lattice structures [43]. As the stress distribution over and inside the saddle is defined using the pressure sensor, consequently, the number and size of piezoelectric layers and the adequate layout of lattice cells can be engineered, by resorting to the data elaboration coming from the prototype equipped for given user. Moreover, the production of lattice structures is based on some layouts, as the Face Centered Cubic (FCC) structure (Fig.9). As a product of the AM technologies, the finalized design of the saddle, with details about its materials, is just sent as a .STL file to the SLA machine, to be manufactured. Using the SLA 3D printers enhances the product customization.

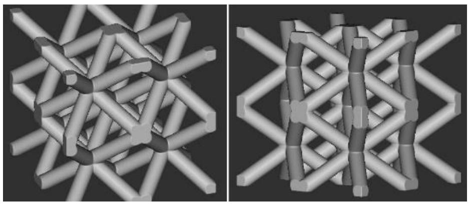

Fig. 9. Face Centered Cubic (FCC) lattice structure.

It is worth noticing that to reduce the discomfort and increase the safety of professional cyclists, facing some risks due to rail breaking in the saddle, those technologies allow embedding even some strain gauges inside the rails. They enable the saddle to measure, store, and transmit the mechanical load's data to a monitoring system, capable of performing some required simulations to predict fatigue failures, and thus to avoid accidents.

VII. The Cyber System

To go back, now, to assets concept, according to the Industry 4.0 paradigms, this saddle is a combination of assets and its Administration Shell (AS) is shown in Fig.10.

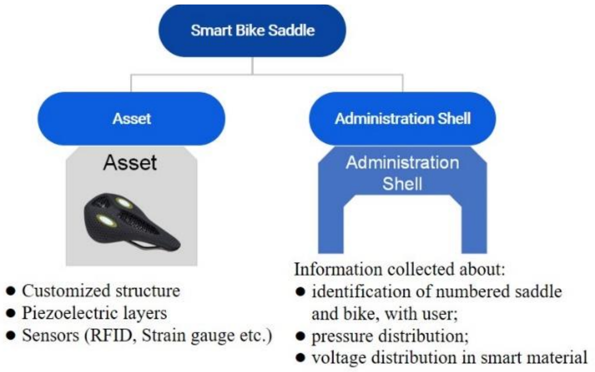

Fig. 10. Asset and administration shell of the smart bike saddle.

The innovative solutions introduced in the saddle design allow the designer managing both the type and instance stages of the product development, as it was described in section II. When the company uses the normal bike saddle covered by a distributed pressure sensor, deals with the development of product in the type stage. The goal is that designer adapts the saddle to each user, and retrieving data of pressure to identify the comfort of cyclist helps this activity. The second stage of the product development begins when the company manufactures the saddle for given user. As Fig.1 shows, this step corresponds to production phase, in the instance stage. The usage phase starts from product delivery and covers the whole service, until the disposal. According to the new concept of saddle proposed, during service, the smart system directly and continuously sends to the company some feedbacks. They help in planning the maintenance actions, and allow introducing some suitable modifications, through the embedded transducers, as the pressure sensor and the strain gauge. A central unit collects those feedbacks, during the type stage and the maintenance phase.

The crucial role of the ASs is appreciated if one considers that there is a repository for those ASs, and for all the versions of the same product [21]. It is accessible by the designer and the manufacturer. As Fig.11 shows, the repository storing the assets contains three ASs, in case of the smart bike saddle, associated to the life cycle. Therefore, throughout the connected network foreseen by the Industry 4.0, all the bike saddle's ASs are connected and updated, as is needed. According to the proposed approach, the ASs operate during the design activity, within the so-called type stage, during the manufacturing they are poorly involved, while after product delivery and during the service, belonging the instance stage, they are intensively used. Interlinking and referencing to each other the Instance/Usage and Type/Usage allow updating both for maintenance goals. The information stored and updated are then used for developing the new versions of product, since the exigencies of customer are identified in operation, elaborated and through the traceability of requirements and functions they are reflected to the Type/Usage step, even by exploiting the tools of the MBSE.

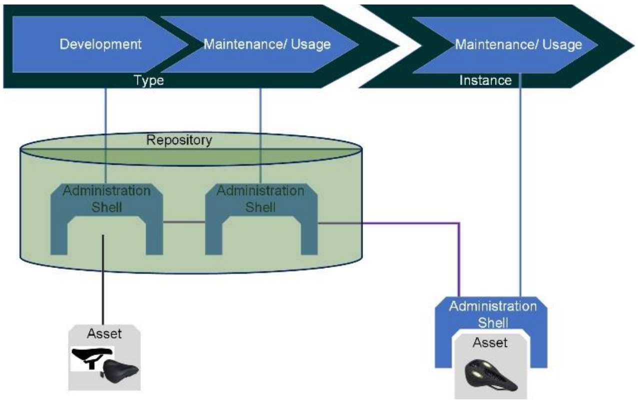

Fig. 11. Connected administration shells of bike saddle in the life cycle.

VIII. CONCLUSION

The product customization can greatly exploit the benefits of the smart manufacturing and smart products, as they have been introduced, during last decades. According to the fourth industrial revolution a new concept of product smartness has been consistently promoted, i.e. the smart product highly adaptable and connected. This trend supports a strong resorting to cyber-physical systems, embedding wireless communication systems. They lead to the decentralized decision-making and the augmented assistance during the product development.

In this study, an example of product customization process supported by the enabling technologies of the Industry 4.0 is proposed. The test case consists of a customized bike saddle. To customize this product for a specific user, the comfort and performance of the saddle must be assured. Those issues are related to a well distributed contact of the user' body with the saddle shell, a limited pressure, a controlled friction and a good damping. In terms of safety, the risk of failure of the saddle rail is still significant. Conceiving the bike saddle as a smart product, a strain gauge can be embedded into rail, to monitor the mechanical load. Moreover, some layers of smart material as piezoelectric sheets embedded into the saddle package can detect the pressure distribution and its amplitude, convert the stress into electric charge for energy harvesting. The information collected can be transmitted to a smartphone for a remote monitoring and data mining. By converse, the new package of bike saddle can be designed and produced by resorting to the AM technologies, to shape the shell properly and to embed sensors. The lattice structures help in tuning the weight and the damping effect of saddle, as well as to enhance the coupling effect of piezoelectric layers. The manufacturer demonstrated that retrieving information from system operation is possible and helps a first refinement of product, when the unfitted saddle is just monitored and then the product is suitably customized in a new version fit-to-purpose as data obtained in operation by user are exploited together with the traceability of requirements and functions assured by tools of MBSE. This approach opens a new application of the MBSE towards a more effective implementation of the Industry 4.0 strategy, in the product lifecycle development, and extends the powerful effects of resorting to digital twin, to cover the system operation.

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