UNIVERSIDADE DE SÃO PAULO

ESCOLA POLITÉCNICA

Beatriz Bretones Cassoli

Product architecture definition and implementation in a Learning Factory focused on Industry 4.0

São Paulo

2019

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Trabalho de Formatura apresentado ao departamento de Engenharia de Produção da Escola Politécnica da Universidade de São Paulo para obtenção do título de Engenheira de Produção.

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Orientador: Prof. Dr. Eduardo de Senzi Zancul

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RESUMO

As fábricas de ensino são importantes ambientes de aprendizagem na medida que melhoram o desempenho na aprendizagem do profissional da indústria. O presente trabalho se insere no contexto da implantação da Fábrica do Futuro USP, que tem como foco a demonstração de soluções da Indústria 4.0 para o processo de produção. Na seção introdutória é apresentada a fábrica de aprendizagem, seu produto-modelo, neste caso um skate, e a visão geral do processo de montagem. Na seção dois é apresentado o problema de pesquisa e os métodos utilizados para alcançar os objetivos definidos. Os principais tópicos relacionados à definição da arquitetura do produto propriamente dito são investigados através de uma revisão de literatura na terceira seção. Os resultados bem como a conclusão e os próximos passos estão descritos respectivamente nas seções quatro e cinco. As principais contribuições deste trabalho são a definição da arquitetura do produto do skate e a assistência e os testes da implementação do sistema de Enterprise Resource Planning na fábrica de ensino.

Palavras-chave: Arquitetura de Produto, Modularidade, Configurador de Produto, Enterprise Resource Planning System, Fábrica de Ensino, Indústria 4.0.

ABSTRACT

Learning factories are important training environments, as they support the education process with hands-on activities that enhance the learning process of industry personnel. The present work is inserted in the context of the setting up of the learning factory "Fábrica do Futuro USP", which is focused on demonstrating Industry 4.0 solutions for the production process. The introductory section presents the learning factory, its model-product, in this case, a skateboard, and provides an overview of the assembly process. Section number two presents the research problem and methodology. The literature review of pertinent topics explored to understand the learning factory's technological context in Industry 4.0, and the subjects necessary to develop the product architecture and assist the Enterprise Resource Planning system implementation are presented in section three. The results, as well as the conclusion and next steps, are described respectively in sections four and five. This work's main contributions are the skateboard product architecture definition and the assistance and testing of the Enterprise Resource Planning system implementation.

Keywords: Product Architecture, Modularity, Product Configurator, Enterprise Resource Planning System, Learning Factory, Industry 4.0.

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LIST OF ABBREVIATIONS

ABDI	Agência Brasileira de Desenvolvimento Industrial
BPR	Business Process Reengineering
CITI-USP	Centro Interdisciplinar em Tecnologias Interativas da USP
CPS	Cyber-physical System
EPUSP	Escola Politécnica da Universidade de São Paulo
ERP	Enterprise Resource Planning
FF	Fábrica do Futuro USP
GE	General Electric
GTI	Grupo de Trabalho para Indústria 4.0
IoT	Internet of Things
IT	Information Technology
LF	Learning Factory
MES	Manufacturing Execution System
PLM	Product Lifecycle Management
RFID	Radio Frequency Identification
R&D	Research and Development
USP	Universidade de São Paulo

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1. Introduction

Changes brought by new technologies, different consumption patterns with declining product lifecycles and a rising number of product variants, increased job rotation and other changing market conditions require continuous learning and developing new competencies in manufacturing (ABELE, 2016, p. 1). Studies have shown that Learning Factories (LFs) offer a relevant approach to support the industry in the current strategic challenges (CACHAY, ABELE, 2012, p. 643). Compared to traditional teaching approaches, LFs allow better application-performance and action-substantiating (required for the understanding of entities and their handling) knowledge (CACHAY et al., 2012, p. 1149–1151). Particularly due to changes brought by the fourth industrial revolution, LFs become of great importance as a way to learn and develop new competencies, such as dealing with high amounts of data and information; using new methods and technologies; and becoming comfortable with changes in the human role in the production process through experimental learning (PRINZ et al., 2016, p. 114).

Learning Factory is a dedicated facility that simulates real production processes and environments and is used to develop competencies of present and future industry personnel (TISCH et al., 2016, p. 1356). The Initiative on European Learning Factories defines the term LF as (Initiative on European Learning Factories, 2012):

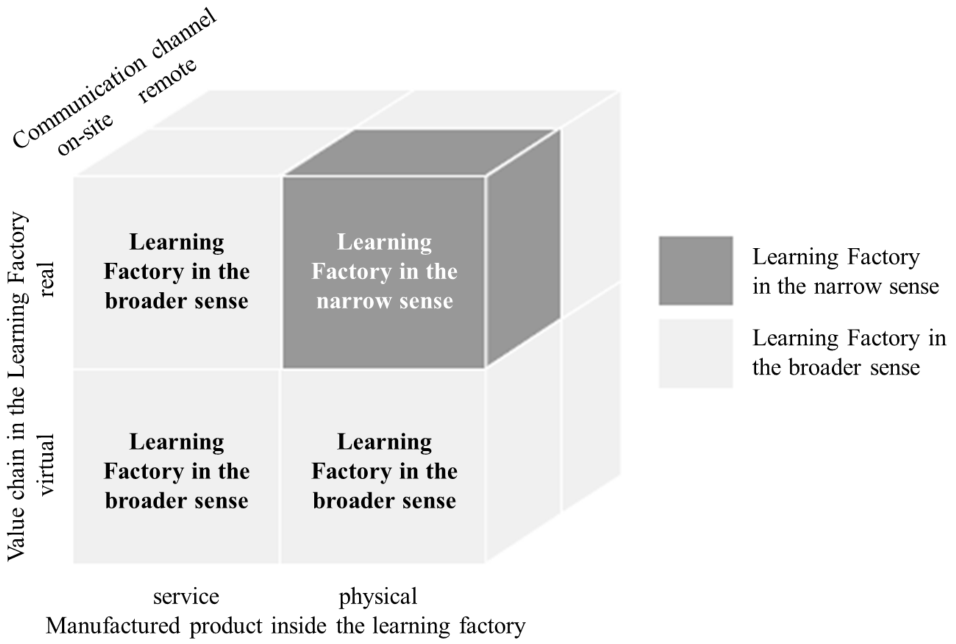
> A Learning Factory is a learning environment where processes and technologies are based on a real industrial site which allows a direct approach to the product creation process. Learning Factories are based on a didactical concept emphasising experimental and problem-based learning.

A LF is also specified by its (ABELE, 2016, p. 1; ABELE et al., 2017, p. 809):

- Processes: real or reality conform, authentic, include multiple work stations, comprise technical and organizational aspects;
- Setting: changeable, simulates a real value chain, real or virtual;
- Product: manufactured in the LF (physical) or a service;
- Didactical concept: consisting of formal, informal and non-formal learning, enabled by own actions of the trainees in an on-site learning approach;
- Purpose: teaching, training and/ or research.

These specifications or key features are also used to classify LFs in the broader sense (light grey cubes) or in the narrow sense (dark grey cube), shown in Figure 1. A LF in the narrow sense is, therefore, the one that manufactures a product, represents a value chain and has its communication channel (through which the knowledge is transmitted) on-site.

Figure 1 - Learning Factories in the narrow and in the broader sense



Source: adapted from (ABELE et al., 2015, p. 2).

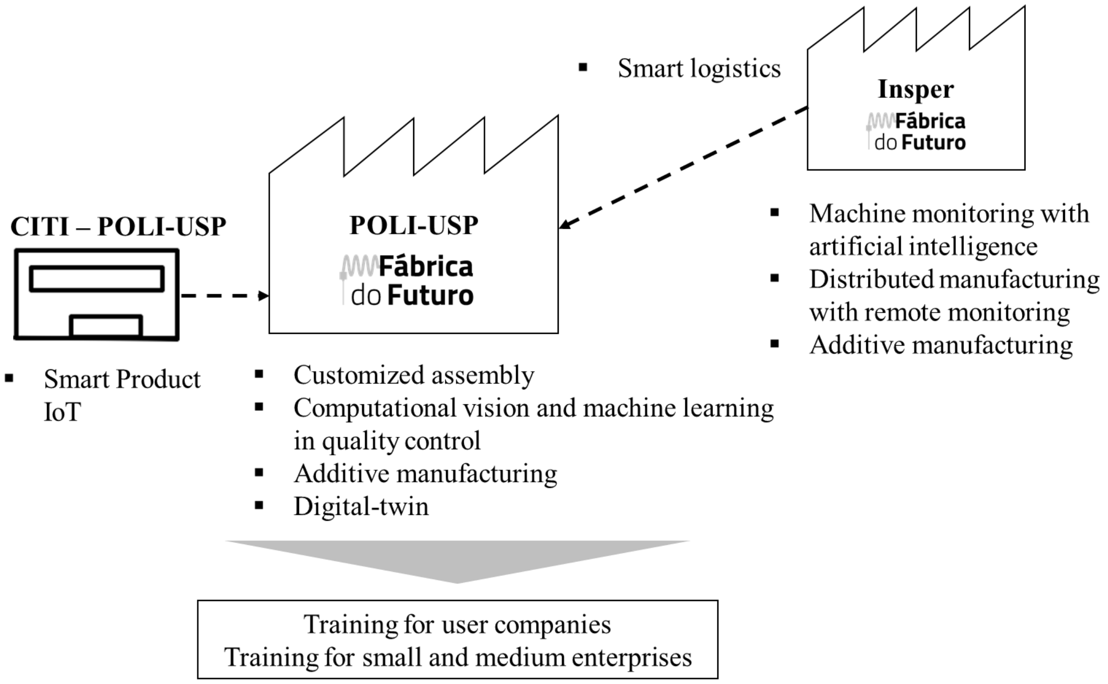
The current work is inserted in the scope of the setting up of a LF, more specifically the LF “Fábrica do Futuro USP” (FF).

Fábrica do Futuro USP

The initiative of the “Fábrica do Futuro USP” (FF) has the objective of establishing a teaching, research, demonstration and testing laboratory for advanced manufacturing, focusing on smart products and smart production. The FF is a project of the Polytechnique School of the University of São Paulo (EPUSP) jointly with the Centro Interdisciplinar em Tecnologias Interativas da USP (CITI-USP), the Insper Institute of Education and Research and more than 15 industry partners.

The main site of the FF is in the InovaUSP, located at the University of São Paulo (USP), campus Cidade Universitária in São Paulo, Brazil. A second site is planned at Insper, which will allow the simulation of typical supply situations between two plants. FF’s sites and their relationships can be seen in Figure 2.

Figure 2 - Fábrica do Futuro USP sites



Source: adapted from FF's publicity material.

The physical product assembled at the FF is a skateboard (shown in Figure 3).

Figure 3 - Skateboard

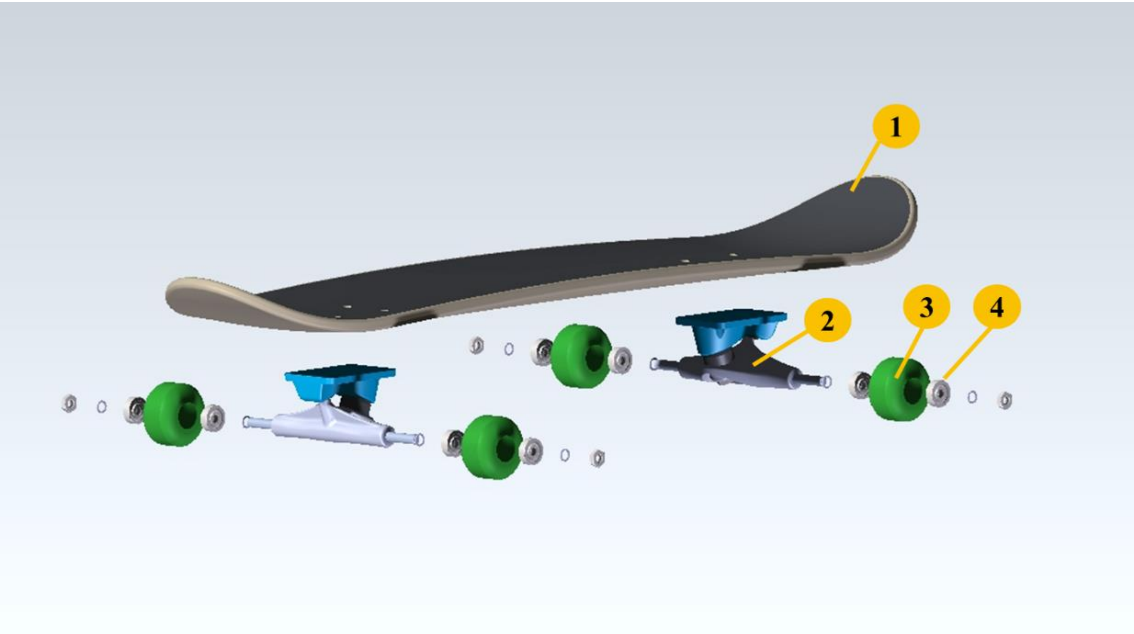
Source: FF's documentation.

The skateboard assembled at the FF has a basic structure – common to all products – and three optional components. The basic structure is shown in Figure 3. The customization of the skateboard allows the choice of the wheel colours, the torque applied to the trucks, and the addition of optional components (connectivity box and the rails). In the future, it will also be possible to choose the content of the sticker glued to the deck, which, for now, is the FF's logo.

Figure 4 and consists of a deck (1), two trucks (2), four wheels (3) and eight bearings (4). The optional components are the connectivity box, the rails, and the deck's sticker.

The customization of the skateboard allows the choice of the wheel colours, the torque applied to the trucks, and the addition of optional components (connectivity box and the rails). In the future, it will also be possible to choose the content of the sticker glued to the deck, which, for now, is the FF's logo.

Figure 4 - Skateboard structure



Source: author's own production based on FF's documentation.

The assembly is performed at FF's main site InovaUSP. The connectivity box's case and the rails (shown in Photograph 1) are also 3D printed at the FF's main site. The connectivity box's electronics are developed at CITI-USP. Eventually, part of the trucks will be manufactured at Insper, exploring a distributed manufacturing scenario with remote monitoring.

Photograph 1 - Rail

Source: author's own production.

The assembly process occurs in four work stations and the disassembly in a fifth work station. In the first work station, the deck is delivered by the milk run trolley. In the future, a QR-Code tag with the product’s identification number is going to be glued on the deck. The deck is positioned on a production device that facilitates the placement of the trucks in its bottom part. Bolts and nuts are used to fix the trucks on the deck. After the quality check guided by a checklist, the unfinished product is placed in the material supply stock of the second work station.

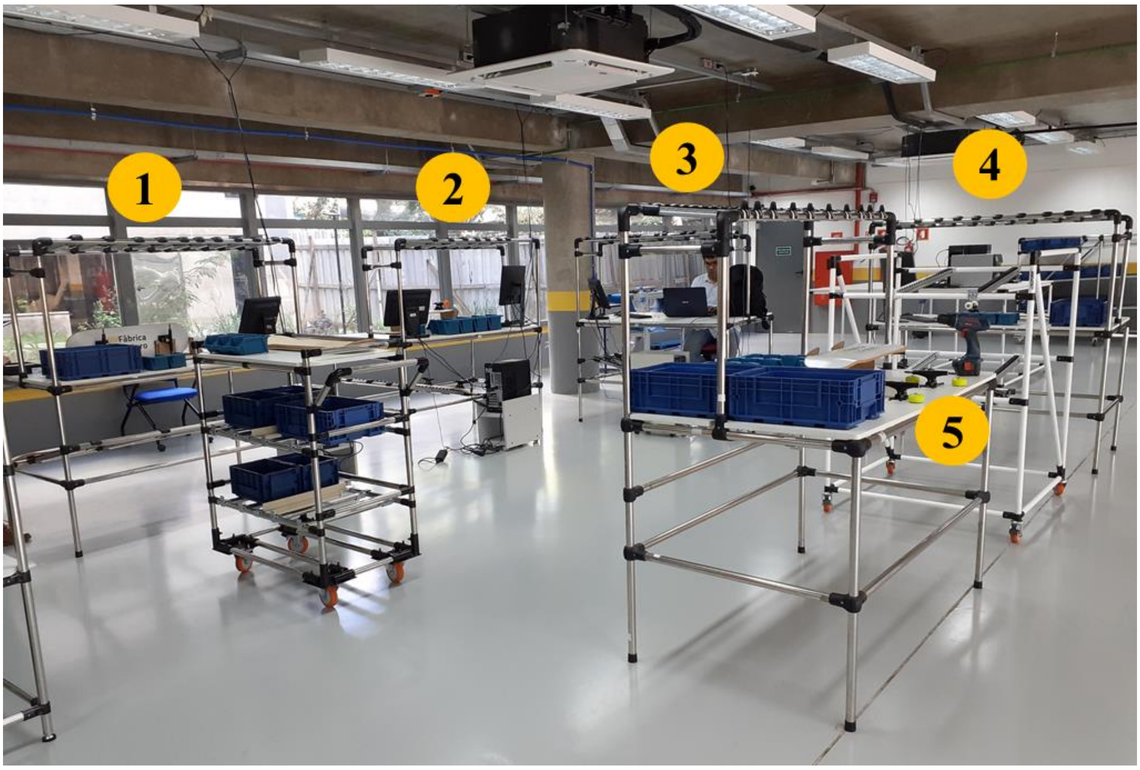
The second work station is used for attaching the wheels and bearings to the skateboard. The front and rear wheels are differentiated and can be personalized with different colours. By using an electric screwdriver, the wheels are fixed to the truck. This part of the assembly is finished by performing a quality check and placing the unfinished product in the material supply stock of the third work station.

The third work station is responsible for applying the specified torque to the trucks. The customer chooses a torque's intensity from a pre-defined range of values. The system translates the selected value into an actual torque applied by a digital torque wrench. After applying the torque and the following quality check, the product is either placed in the finished goods inventory or placed in the material supply stock of the fourth work station.

The fourth work station is where the optional features of the skateboard are added to the product. Both the connectivity box and the rails are produced within the factory in the 3D-printers located at the facility.

The fifth and last work station is where the disassembly occurs and where the skateboard's parts are returned to the inventory to be re-used. Photograph 2 presents the four assembly work stations and the fifth work station where the disassembly of the skateboard occurs.

Photograph 2 - Assembly line



Source: author's own production.

The scope of this work is inserted in the context of the FF implementation. More specifically, this work aims to define the product architecture and to support the implementation of the Enterprise Resource Planning (ERP) system at FF.

The second section presents the work's methodology, the research problem and the chosen methods for reaching the research objectives. The third section presents a literature review on Industry 4.0, mass customization and other relevant topics related to product architecture (i.e. product modularity and product variety management). The third section provides an overview of Enterprise Resource Planning systems and the challenges brought by the fourth industrial revolution. The final section concludes the work and suggests potential future research.

2. Methodology

According to Kothari (2004, p. 19) it is possible to group general research objectives into four broader categories:

1. Exploratory or formulative research studies: research done in order to gain familiarity with a phenomenon or new insights;
2. Descriptive research studies: studies that portray the characteristics of a particular individual, situation or group;
3. Diagnostic research studies: studies done in order to determine the frequency with which something occurs or the frequency with which it is related to something else;
4. Hypothesis-testing research studies: research done in order to test the causal relationship between variables.

This work fits into the first category. This research aims at collecting knowledge about certain topics, understanding them, achieving new insights and applying them to a practical case. As discussed in the introductory section, the research problem that defined the goals of this work is proposed given the context the learning factory “Fábrica do Futuro USP” implementation.

A research problem is “one which requires a researcher to find out the best solution for the given problem, i.e., to find out by which course of action the objective can be attained optimally in the context of a given environment” (KOTHARI, 2004, p. 42). The definition of the research problem followed the successive steps: (i) assessing the implementation standpoint by the time this work started; (ii) defining the work to be done and steps in order to advance with the implementation process; (iii) assigning roles and responsibilities to the team involved in the implementation; (iv) defining the research question and scope for this work specifically; (v) defining the work plan.

The first steps were conducted together with Professor Eduardo Zancul, advisor to this work, and with FF’s student team working in the FF implementation. Table 1 summarizes the Industry 4.0 demonstrators formerly chosen to be implemented.

Table 1 - Industry 4.0 demonstrators of the Fábrica do Futuro USP

ID	Category	Demonstrator	Physical aspect
1	Smart production	Customized assembly	Assembly line/ work stations, ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System) software
2	Smart production	Quality control based on computer vision and machine learning	Smart camera from MVISIA
3	Smart production	Machine monitoring and artificial intelligence applied in predictive actions	Data acquisition in machining processes
4	Smart production	Customized production in small batches through additive manufacturing	3D printers
5	Smart production	Components identification through RFID technology	RFID printer
6	Smart production	Distributed manufacturing with remote monitoring	Connected 3D printer
7	Smart production	Indoor localization	Beacons
8	Smart production	Augmented reality	Tablets
9	Smart production	Intelligent energy management	Monitor
10	Smart product	Digital Twin	Product Lifecycle Management (PLM) software
11	Smart product	Project for disassembly - Circular Economy	Work station number 4

Source: author’s own production based on FF’s documentation.

Having listed all the demonstrators to be implemented, the demonstrator 1 (Customized assembly) is the one assigned to delineate this work’s scope. Since fabrication tasks and their takt, work stations, and other matters related to the factory layout had been contemplated in previous research, this work's focus lays upon the product architecture definition, its implementation on the Enterprise Resource Planning (ERP) system and on the product configurator necessary to achieve a customizable assembly. From this analysis, the research problem of this work is defined as follows:

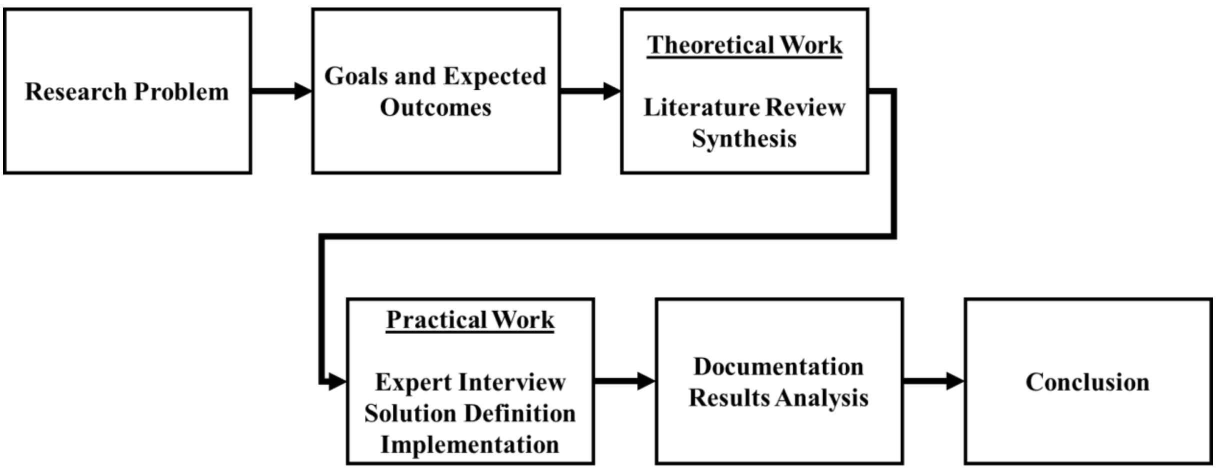
Defining and implementing the skateboard product architecture and product configurator in an Enterprise Resource Planning (ERP) system to operate in the learning factory "Fábrica do Futuro USP".

Conducive to solving this research problem and defining the scope of this work, certain goals and expected outcomes are also enunciated:

- Understanding the physical product assembled at the FF: the skateboard;
- Understanding the concepts of product variety management, product architecture, product modularity, part identification numbering, product personalization, mass customization, and ERP systems;
- Applying these concepts to the learning factory and defining:
  - The skateboard (modular) product architecture;
  - The customizable product components and parameters;
  - The product identification and parts numbering patterns.
- Assisting and testing the ERP implementation in the learning factory;

The work plan that guided the development of this work is presented in Flowchart 1.

Flowchart 1 - Work plan



Source: author's own production.

Having clarified the research problem, the goals and expected outcomes were derived from it. In order to accomplish them, a literature review synthesizing the relevant topics was first carried out. The practical work, which is of utmost importance for this work, was developed beginning with an expert interview – for industry input purposes – followed by the solution definition of each specified expected outcome and their subsequent implementation. The work documentation and the consequent results analysis are important to consolidate the work performed and make it available for future consultation.

The literature review was carried out using three different sources. The first source, a keywords search in Google Scholar led to papers and books previously published on the specified topics. The list of keywords used in the search can be seen in Table 2. In order to select papers published in acknowledged journals, the Scimago Journal & Country Rank (Scimago Institutions Rankings, 2019) for the engineering area was used as guidance. The second source consists of papers and a master's dissertation suggested my Professor Eduardo Zancul. The third source of information was websites – from a skateboards retailer and the Brazilian government's initiative for Industry 4.0's official website – and newspaper publications, that were consulted for additional information.

Table 2 - Keywords

Topic	**Keywords**
Industry 4.0	Industrie 4.0
	Industry 4.0
	Indústria 4.0
	Industrial internet
	Cyber-Physical Systems
Customization	Mass customization
	Product customization
	Product variety management
	Product configurators
	Product modularity
	Product architecture
Enterprise Resource Palanning systems	Enterprise Resource Palanning systems
	ERP
	ERP success factors

Source: author's own production.

The product architecture definition and its implementation in the ERP system were done based on the knowledge acquired through the literature review and through the expert interview.

3. Literature Review

This section presents the literature review of pertinent topics to understand the learning factory's technological context in Industry 4.0, and the subjects necessary to develop the product architecture and assist the Enterprise Resource Planning system implementation.

The first topic covered is Industry 4.0. Emerging technologies and increasing manufacturing flexibility bring efficiency gains, which allow the realisation of market trends, such as mass customization. The consequent increase in product complexity and variants number, make product variety management and product configurators of great importance to the manufacturing firm. In this context, ERP systems play an important role in organizing product information and assisting the customer's journey towards product customization. The current challenges of ERP systems brought by the fourth industrial revolution are presented at the end of the section.

3.1 Industry 4.0

The term industry 4.0, also called the fourth industrial revolution, was first introduced in the Hannover fair (Germany) in 2011 as a paradigm shift in the industry, allowing new business models through Cyber-Physical Systems (CPSs) (KAGERMANN, LUKAS, WAHLSTER, 2011, p. 1). The initiative, supported by the German government under a "High-Tech Strategy 2020 Action Plan", aims at achieving a higher level of operational efficiency and productivity, as well as a higher level of automatization (THAMES, SCHAEFER, 2016, p. 13).

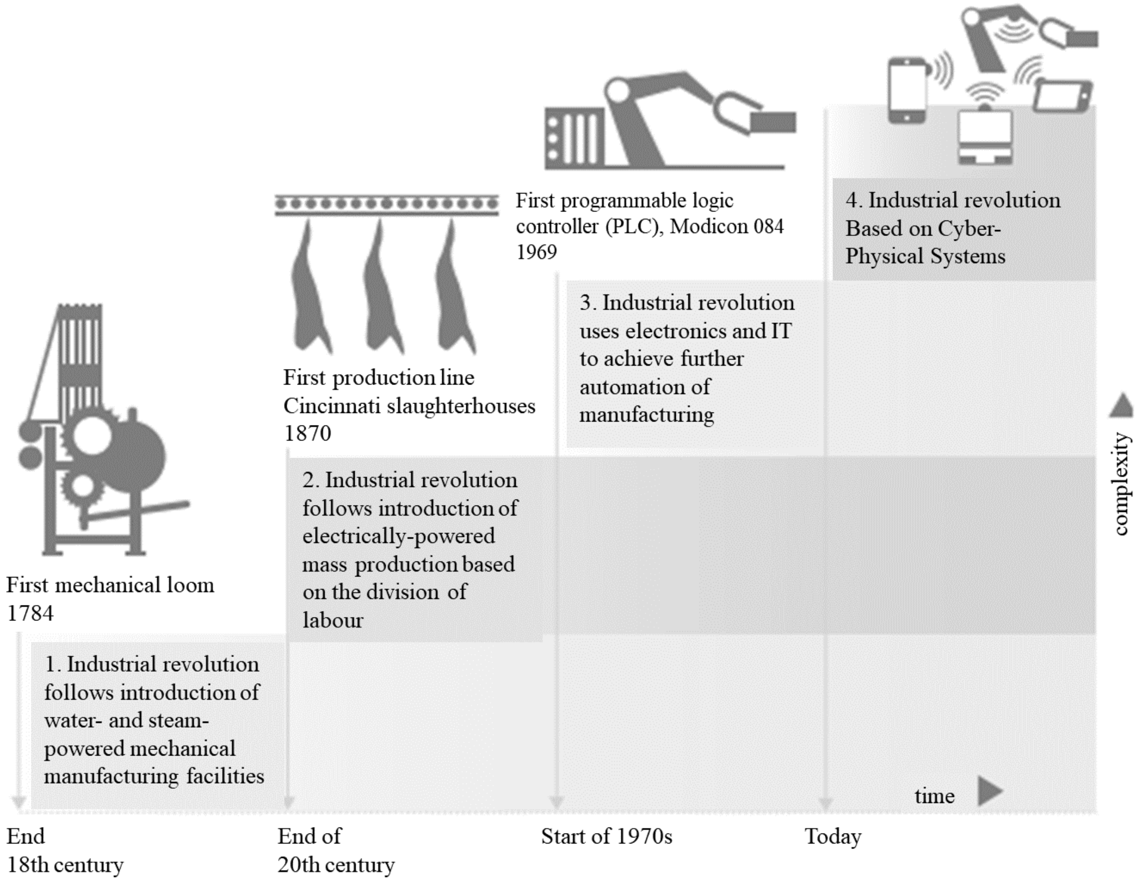
A similar concept was brought by General Electric (GE) in the United States when referring to its future business orientation: the "industrial Internet" (LEBER, 2012). GE's industrial Internet is based on three key elements (EVANS, ANNUNZIATA, 2012, p. 3):

- Intelligent machines: use of sensors, controls and software applications to connect machines, facilities, fleets and networks;
- Advanced analytics: use of physics-based analytics, predictive algorithms, automation and deep domain expertise;
- People at work: connecting people inside GE in order to support design, operations, maintenance and service.

The Chinese government also showed support towards the advancement of similar efforts in the country through the initiative "Internet +" (WANG et al., 2016, p. 1). In Brazil, the government has identified key technologies to drive the fourth industrial revolution in the country. Namely, additive manufacturing, artificial intelligence, synthetic biology and cyber-physical systems (ABDI - Agência Brasileira de Desenvolvimento Industrial, 2019). The Brazilian government sees the migration of industry to the 4.0 concept as a way of reducing industrial costs, through efficiency gains, reduced machine maintenance costs and energy consumption, estimated in R$ 73 Billions per year. The Brazilian Ministry of Industry, Foreign Trade and Services has shown its support to the initiative and established in July 2017 the "Grupo de Trabalho para a Indústria 4.0" (GTI 4.0), a work-group to draw up a proposal for the Industry 4.0 national agenda. The group has more than 50 institutions both from the public and private sector and works in partnership with public and private banks and development agencies to ensure a range of financing options accessible to different companies and needs (ABDI - Agência Brasileira de Desenvolvimento Industrial, 2019).

Figure 5 presents an overview of the past industrial revolutions until the fourth one discussed in this section. The first industrial revolution starts in the 1780s with the mechanical looms driven by steam engines; fabric production slowly migrated from private homes to central factories, increasing productivity. The second industrial revolution, that started almost 100 years later in Ohio, United States of America, had its peak with Ford's production line, based on the division of labour and use of conveyor belts. The third industrial revolution is characterized by the use of electronics and Information Technology to achieve further automation of manufacturing, leading to flexible and efficient automation systems (DRATH, HORCH, 2014, p. 56).

Figure 5 - Industrial revolutions



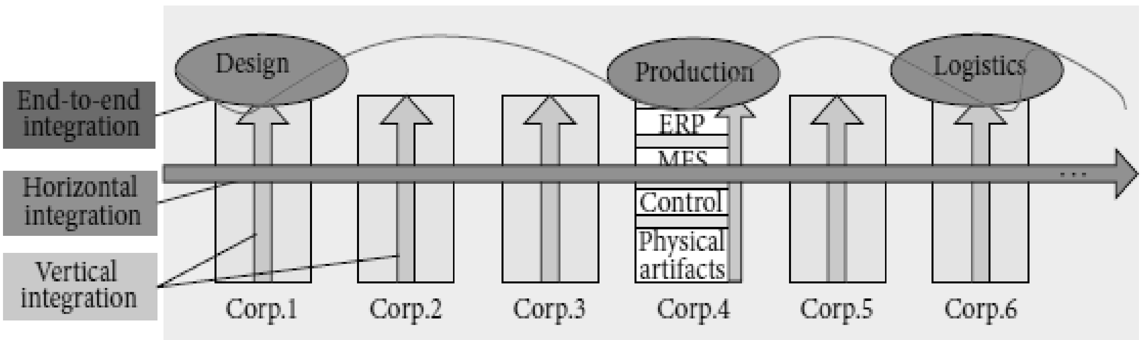
Source: adapted from (KAGERMANN et al., 2013, p. 13).

Industry 4.0 is based on a series of new technologies and their combined use to generate new production possibilities, particularly the use of Radio Frequency Identification (RFID), Enterprise Resource Planning (ERP) systems, Internet of Things (IoT), cloud-based manufacturing, and social product development (LU, 2017, p. 1). Industry 4.0 is, therefore, highly based on integration. This integration is divided in the literature into three different levels, also shown in Figure 6:

- Horizontal integration: refers to inter-organizational integration, creating an efficient ecosystem and allowing new value networks and new business models (WANG et al., 2016, p. 2). It is the integration across the value chain, both the cross-company and the company-internal cross-linking of value creation modules (STOCK, SELIGER, 2016, p. 537);

- Vertical integration: integration of actuators, sensor signals and the ERP level inside a factory in order to enable a flexible and reconfigurable manufacturing system. In this context smart products and smart machines, forming a self-organized system, are able to adapt and be dynamically reconfigured (WANG et al., 2016, p. 2).
- End-to-end engineering integration: cross-linking and digitalization of all phases of the product life cycle (STOCK, SELIGER, 2016, p. 537). Encompasses all activities involved in the product development process – from customer requirement definition, product design and development, production planning, production engineering, manufacturing, sales, maintenance, and recycling – are integrated making use of a consistent product model in all phases (WANG et al., 2016, p. 3).

Figure 6 - Kinds of integration

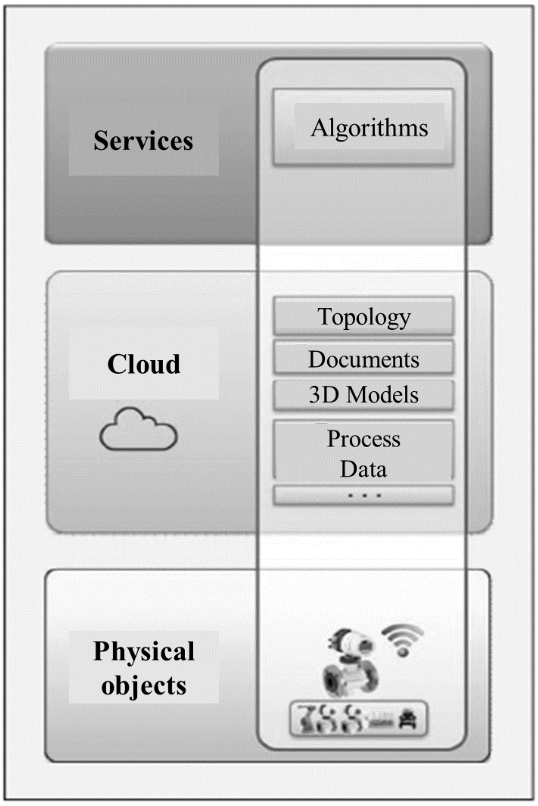


Source: (WANG et al., 2016, p. 2).

The cross-linking and digitalization are enabled by the use of information and communication technologies embedded in the cloud, realized by Cyber-Physical Systems (CPS). CPSs are "integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa" (LEE, 2008, p. 363). In these systems there is a coupling between cyber and physical, whose operations are monitored, coordinated, controlled and integrated by a computing and communication centre (RAJKUMAR et al., 2010, p. 731).

A CPS operates in three levels: the physical objects equipped with sensors, data models of the physical objects in a network infrastructure and services (algorithms) to be used with the available data (DRATH, HORCH, 2014, p. 57). Figure 7 illustrates the three levels that form a CPS in an Industry 4.0 scenario.

Figure 7 - Three levels of CPS



Source: adapted from (DRATH, HORCH, 2014, p. 57).

Computation devices, embedded sensors and actuators allow monitoring and coordinating operations of physical processes in real time, leading to more responsiveness and effective systems. This trend in the industry is supported by the increase of low-cost sensors of smaller size, the availability of low-cost, low-power, high-capacity, small size computing devices, wireless communication, large internet bandwidth, improvements in energy capacity and energy generation (RAJKUMAR et al., 2010, p. 731). There are currently many challenges for the future of CPS and its implementation in factories. Uncertainty and noise in the physical environment, the lack of perfect synchronisation across time and space, potential failures of components in both cyber and physical worlds, security and privacy requirements, increasing system complexity and system stability are a few of the identified matters that have to be addressed for CPS (DRATH, HORCH, 2014, p. 58; RAJKUMAR et al., 2010, p. 731). In the so-called Smart Factories, CPS operates as the “nervous system” of the factory, the manufacturing equipment is characterized by automated machine tools and robots, being able to adapt to changes (KAGERMANN, LUKAS, WAHLSTER, 2015, p. 1; STOCK, SELIGER, 2016, p. 539). Besides the flexible machinery, a smart factory is also characterized by a wider range of resources that are available to produce multiple types of small-lot products, by a dynamic routing that changes according to the demand of each product type, by a network infrastructure that connects machines, products, information systems and people, by a dynamic systems with smart entities that organize and cope with themselves, and by a large amount of data generated by the smart artefacts and their interactions (WANG et al., 2016, p. 6).

The promising shift in production efficiency and flexibility contribute to the fast adaptation and response to market changes. An evolving trend is mass customization, with products being manufactured in batch size one according to customers' requirements, that can be made possible with the flexible factories conceptualized through smart factories (STOCK, SELIGER, 2016, p. 539).

3.2 Customization

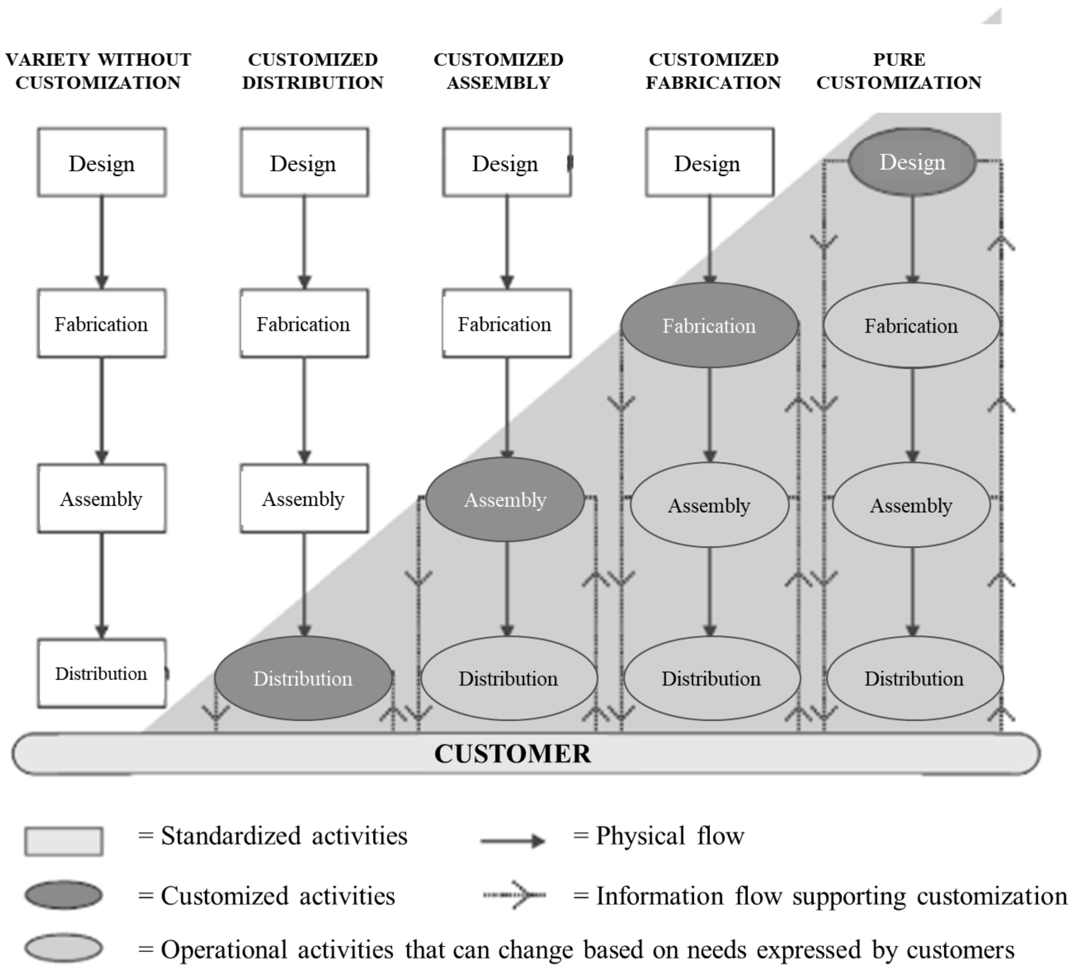
Mass customization is a concept that emerged in the late 1980s and is related to the ability to satisfy customer needs, through product customization, while keeping near mass production efficiency (DA SILVEIRA, BORENSTEIN, FOGLIATTO, 2001, p. 1). Mass customization, therefore, attempts to make feasible manufacturing products with a high degree of variety without dramatically raising end-product prices to customers, and thus sustaining the firm competitiveness. The recent developments in flexible manufacturing technologies and information technologies have made possible to customize products at lower costs, which increased the attention paid to mass customization (MIKKOLA, 2007, p. 58).

Salvador, Holan and Piller (2009, p. 71) describe mass customization as a strategic mechanism that, when appropriately understood and deployed, can be applicable to most businesses. It should be a process for aligning an organization with its customers' needs. The authors identify a set of three organizational capabilities, which are neither product nor industry specific, that make mass customization viable (SALVADOR, HOLAN, PILLER, 2009, p. 73–75):

- Solution space development: ability to identify the product attributes along which customer needs diverge. It can make use of innovation tool kits, such as software, to collect customers' preferences and allow them to highlight possibly unsatisfied needs;
- Robust process design: reuse or recombine existing organizational and value-chain resources to fulfil a stream of differentiated customers' needs;
- Choice navigation: support customers in identifying their own solutions while minimizing the complexity and burden of choice.

Forza and Salvador (2006, p. 10) defines customization in terms of four operational activities of a manufacturing firm: design, fabrication, assembly and distribution. A product is customized when one or more of these activities are conducted based on requirements expressed by the customer. Figure 8 presents a spectrum of product customization by adding customized activities in different stages of the product configuration. Variety without customization is the case when there is no customized activity in the operational activities that deliver a product to the consumer. Customized distribution is characterized by selecting the product variants that arrive at each customer/ location. Customized assembly allows the consumer to select which variants (from a set of options) will be incorporated in the final product. Customized fabrication involves the customer in the fabrication stage, and thus allows a higher degree of customization. Finally, pure customization is the higher degree of customer involvement, for each new order, the product is design based on the provided requirements (FORZA, SALVADOR, 2006, p. 11).

Figure 8 - Scope of product configuration



Source: adapted from (FORZA, SALVADOR, 2006, p. 10).

The underlying assumption in customization and offering a great number of variants of a product to customers is that, under these circumstances, they are capable to appreciate product utility and decide to buy it: “a customer buys a product, not only if he can choose among many variants, but also and especially if he has a chance to express his needs and is then offered a product that satisfies them ” (FORZA, SALVADOR, 2006, p. 9–10). In case this assumption is satisfied – when the customer can indeed see the benefits of the product – a customized product can be a “winning key” for order acquisition.

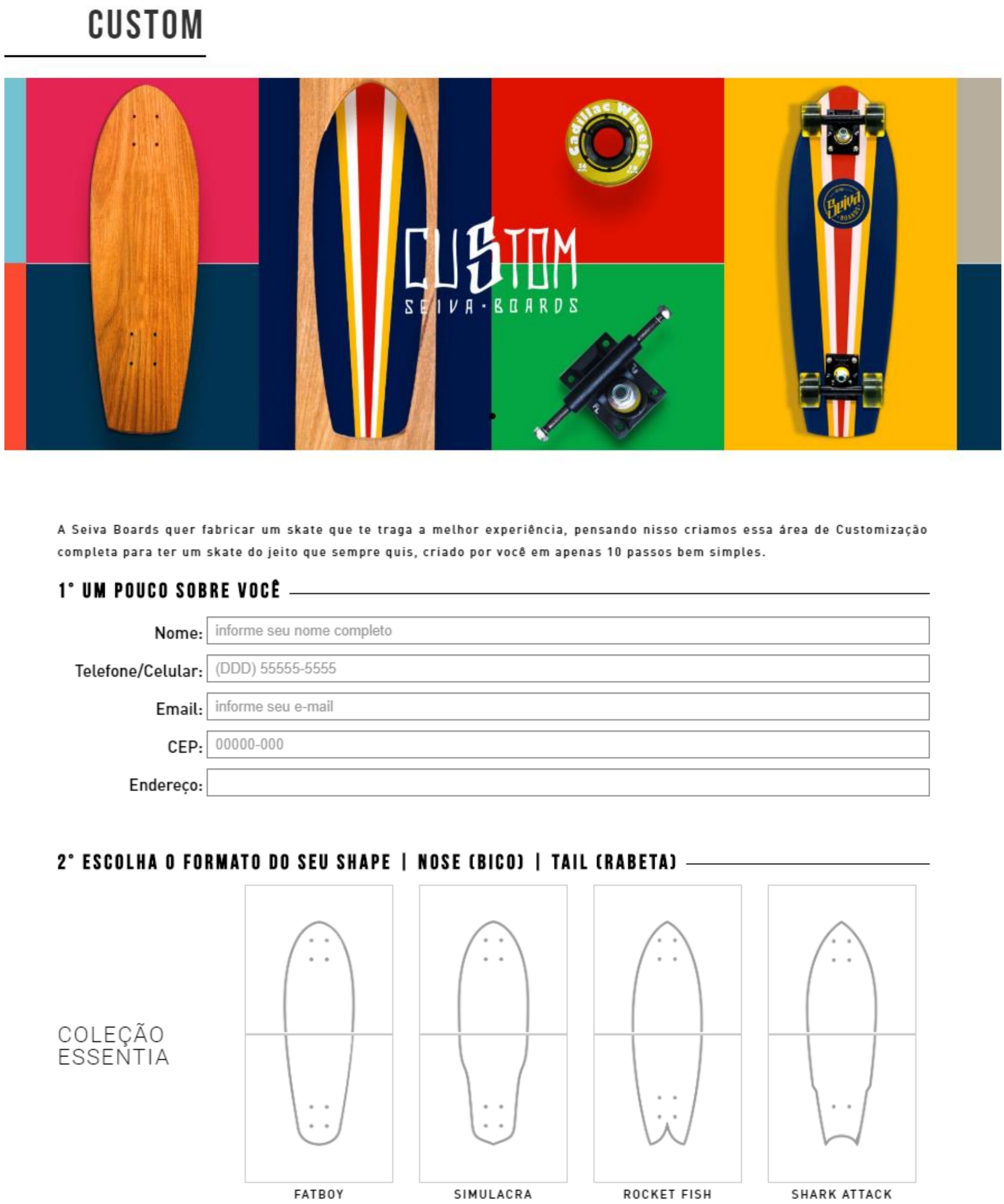
The product variety is defined as the assortment of products that a production system provides to the market, and it is only meaningful to consumers if the attributes of the product from which the user derives a benefit vary in some way (ULRICH, 1995, p. 428).

As competition between firms become more intense, the need for differentiation and for key competitive advantages become more critical to ensure firm survival. In order to attract more buyers and secure market share firms are faced with the challenge of putting the customer in the centre of the organization and asking: what does my customer need? What is value to my customer? Customers’ demands for new product functions and features, different regional requirements, larger number of market segments with specific needs and certification specifications are some of the sources of complexity that this exercise has to manage (ELMARAGHY et al., 2013, p. 629). The development of products should then translate the identified heterogeneous needs into product features and functions. This process often leads to an increase in product variety, i.e. the number of different products offered to customers, a wider range of product customization and personalization (SALVADOR, FORZA, RUNGTUSANATHAM, 2002, p. 549).

However, more variety does not necessarily mean an increase in sales and revenue. The so-called “paradox of variety” shows that offering a wider range of options can cause frustration and dissatisfaction with the complexity, impacting the percentage of customers who make a purchase. The retailer should be able to control both the way the information is presented and the input the consumer provides when evaluating the available attributes and alternatives (HUFFMAN, KAHN, 1998, p. 492). In this context, two difficulties arise: it becomes more difficult for the customer to choose the product attributes that best fulfil his needs; and it becomes more difficult for the company to collect, store and process the larger amount of data describing customers’ orders. For the first case, it is necessary to provide the customer with more information about the production displayed in a proper way in order to facilitate the decision process. As for the second case, the company requires specific tools for managing this information, that most of the times has to be translated into appropriate product documentation then to be used on the shop floor to manufacture the ordered product variant (FORZA, SALVADOR, 2002, p. 97–98).

Product configurators are information systems that aid customer selecting the specification of the product configuration besides the creation and management of configuration knowledge (KRISTJANSDOTTIR et al., 2018, p. 196). Product configurators are developed to resolve the difficulties mentioned above related to providing information to customers and managing product configuration information. A configurator checks the specification of a product regarding completeness (i.e. that all the necessary selections are made) and regarding consistency (i.e. that no rules are violated) based on the configuration knowledge stored in the configurator in the form of configuration models. They also assist customer in the configuration task, by providing a step-by-step selection process among predefined attributes options (HEISKALA, 2007, p. 14), and in many cases are used to automate the process of quotation, sales prices, bills of materials and other production specifications (HAUG, HVAM, MORTENSEN, 2011, p. 197). Figure 9 and Figure 10 show parts of the product configurator of a Brazilian skateboard retailer, the Seiva Boards, which supports a high degree of product customization and illustrates the forenamed features.

Figure 9 - Example skateboard configurator 1/2



Source: (Seiva Boards, 2019).

Figure 10 - Example skateboard configurator 1/2

Source: (Seiva Boards, 2019).

Product configurators, when successfully implemented, help companies achieve significant lead time and man-hour reductions in the quotation and production preparation-related processes (HAUG, HVAM, MORTENSEN, 2011, p. 205; HVAM et al., 2013, p. 336). Research has also shown improved quality of product specifications by the use of configurators, that lower the risk of losing a strategic competence due to the departure of a key sales employees as the customisation knowledge is transferred to the configurator system (FORZA, SALVADOR, 2002, p. 98). Other cited benefits of product configurators include quality improvements (such as the reduction of assembly errors) (HVAM, 2006, p. 424) and the improvement of product-related and experience-related benefits perceived by customers (TRENTIN, PERIN, FORZA, 2013, p. 442).

The implementation of a product configurator system also presents many challenges, according to Kristjansdottir et al. (2018, p. 199) the main ones fit under the following categories:

- IT-related: technical challenges related to IT systems, such as software personalization, design of a user interface, scope expansion, interaction with software suppliers, and functionalities;

- Product modelling: challenges related to the formalization of product knowledge and how it is embedded in the configurator;
- Organizational: challenges and difficulties related to change management, management support and resources allocation;
- Resource constraints: scarcity or inadequacy of personnel to model the configurator, gather and provide information, and reliance of resources;
- Product-related: complexity of product structure and frequent change in products;
- Knowledge acquisition: especially in the development and maintenance phases of the configurator, difficulties in knowledge consolidation and availability of information.

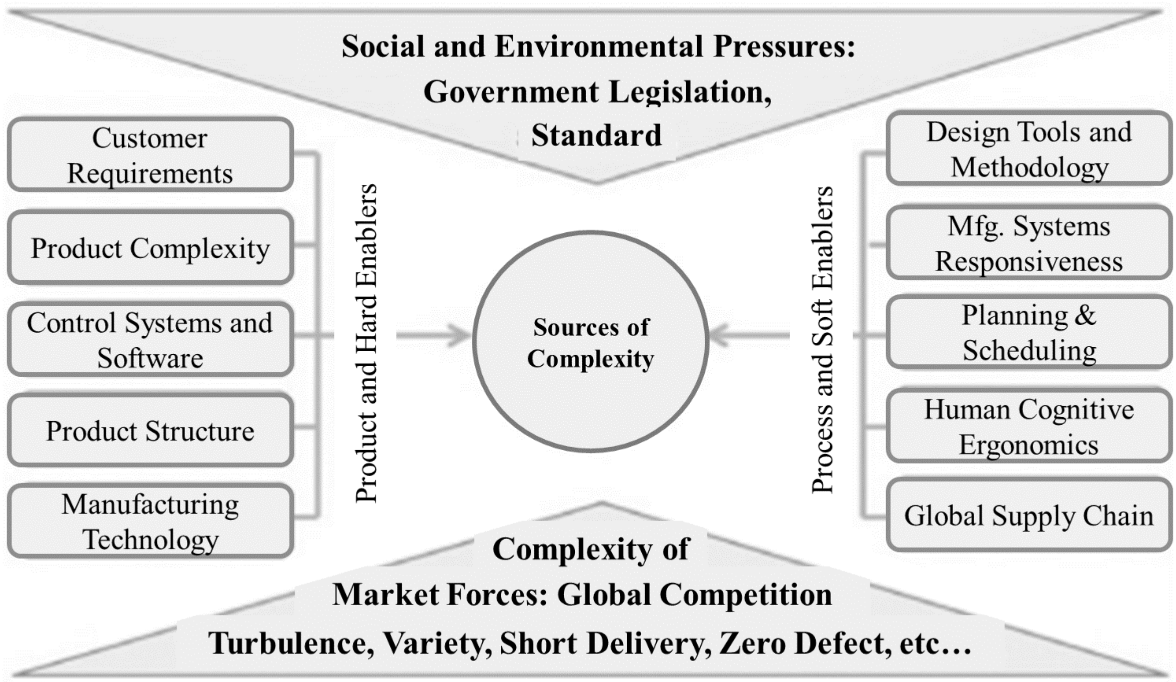
Kristjansdottir et al. (2018, p. 206) concludes that organizational, knowledge acquisition and product modelling are the most challenging categories, resource constraints, IT-related, and product-related challenges are less important, and the product-related category is of very low importance.

The core of a product configuration system is the product model, which is the logic structure that provides the product characteristics (commercial and technical) and the constraints between these characteristics. The product model has the rules that allow building the product variant and its documentation (bills of materials, routings, diagrams, etc.) based on the input provided by the customer (FORZA, SALVADOR, 2002, p. 96). The literature also separate configurators into two logic structures (TRENTIN, PERIN, FORZA, 2011, p. 261): the sales configuration model – a representation of the company's offerings, its product space, and the procedure to generate product variants inside that space, which can include sequence of questions, images and representations of the product, and other resources to guide the customers – and the technical configuration model – responsible for linking the sales configuration model with the data describing each product variant from a manufacturing perspective.

3.3 Product Variety Management

The challenge of managing variety goes beyond selecting the right amount of options to end consumers. Variety occurs throughout the entire product lifecycle, increasing manufacturing complexity, impacting costs, logistics and pre- and after-sales services (ELMARAGHY et al., 2013, p. 630). Products become more complex as they are made not only with mechanical and electrical components, but also software, control modules, human-machine interfaces, and are connected on-line following the "internet of things" trend for real-time reporting and diagnosis (ELMARAGHY et al., 2012, p. 793). Figure 11 summarizes the sources of manufacturing technology, including the ones that are the focus of this work: product complexity and product structure.

Figure 11 - Drivers of manufacturing complexity



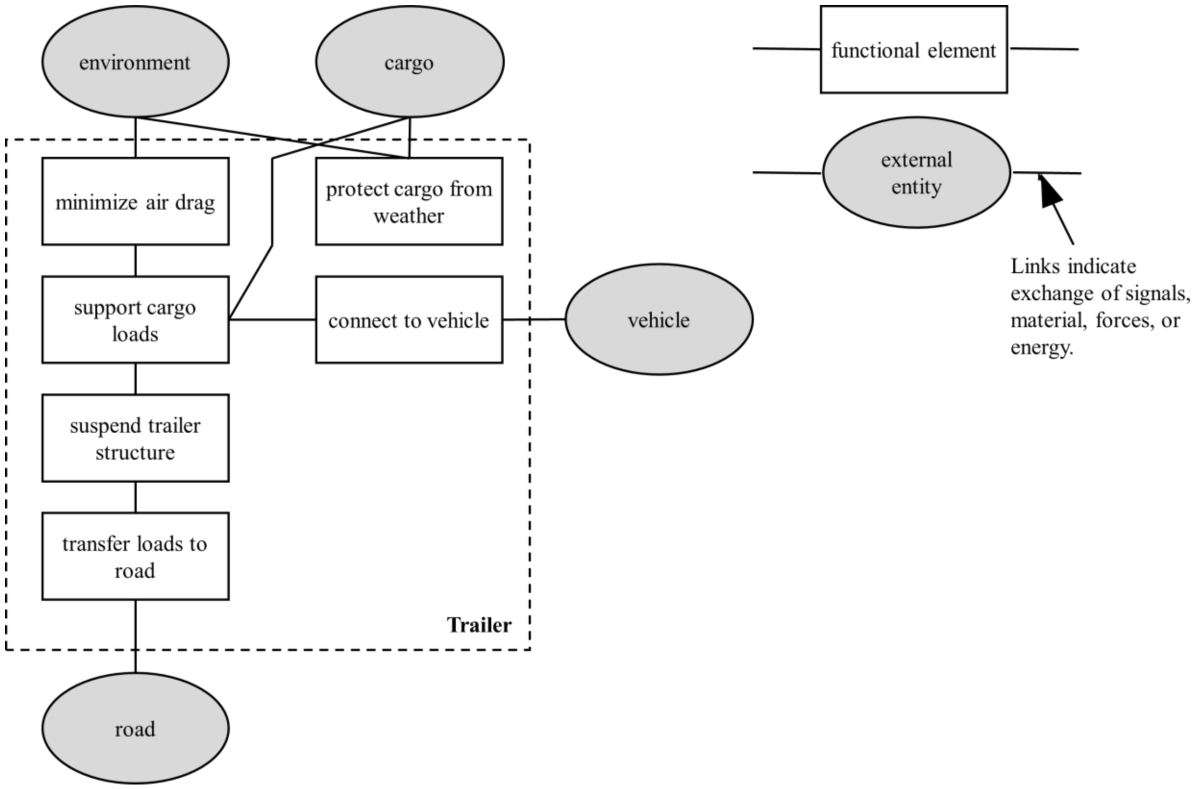
Source: adapted from (ELMARAGHY et al., 2012, p. 794).

Variant multiplicity can be originated from external causes, like the ones previously mentioned and which the manufacturer does not have control, or they can be originated from internal causes, which result from organizational and technical deficiencies that produce an unnecessary number of variants at the parts level (ELMARAGHY et al., 2013, p. 631). The following subchapters present approaches for achieving product variety efficiently, including product architecture and product modularity, in order to reduce internal causes for variant multiplicity.

3.3.1 Product Architecture and Product Modularity

Product architecture is the visual scheme that links product functions to its physical components and interface specifications. The product architecture has, according to Ulrich (1995, p. 420), a threefold purpose: presenting the arrangement of functional elements, mapping from functional elements to physical components, and specifying the interfaces among interacting physical components. Product architecture also facilitates research and development (R&D) decisions such as ease of product change, internalization or externalization of development, ability to obtain a certain degree of product performance, and guide the management and organization of product development (ULRICH, 1995, p. 419). For illustrative purposes, the product architecture of a trailer presented in Ulrich (1995, p. 420–422) is reproduced in Flowchart 2.

Flowchart 2 - Function structure of a trailer



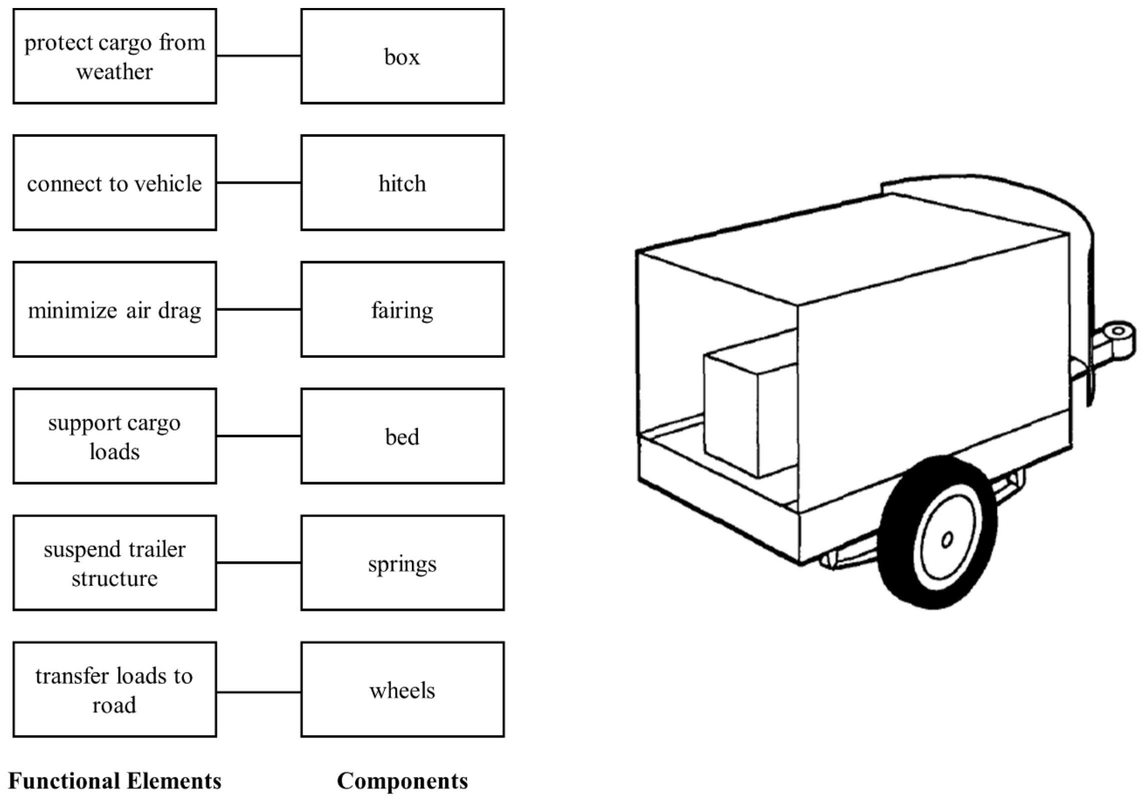
Source: adapted from (ULRICH, 1995, p. 420).

Modularity is a type of design which intentionally allows independence (or loose coupling) between components through interface standardization. According to Ulrich (1994, p. 220) a product cannot be classified as either modular or not, they can present a higher or lower degree of modularity in its design. Two characteristics define then the degree of modularity of a product:

1. Similarity between the physical and functional architecture of the design.
2. Minimization of incidental interactions among physical components.

A modular product architecture is a form of product design that makes use of standardized interfaces between components in order to build a flexible product architecture (SANCHEZ, MAHONEY, 1996, p. 66). A modular architecture is only possible when each functional element of the product is linked to a physical component (one-to-one mapping) and when the interfaces between components are de-coupled (a change to one component does not require a change to the other component in order for the overall product to work properly) (ULRICH, 1995, p. 426). Different types of modularity are observed in products (ULRICH, 1995, p. 424): (1) slot modularity in which the interface between component types are different, so components from different types cannot be interchanged (for example an automobile radio, which implements one function and is de-coupled from other components, but its interface differs from the interface of the other components in the vehicle). (2) bus architecture, in which there is a common "bus" or platform that allows other components to be attached on it with the same interface (for example, an expansion card for a personal computer). (3) sectional architecture, for which all components have the same interface and there is no connecting element between the components (e.g. some piping systems). An example of a one-to-one mapping of functional elements to physical components and the related product drawing is reproduced in Figure 12.

Figure 12 - A modular trailer architecture exhibiting a one-to-one mapping from functional elements to physical components



Source: adapted from (ULRICH, 1995, p. 421).

Some of the potential benefits brought by a modular product architecture are identified by Ulrich (1994, p. 223–225) and summarized here:

- Component economies of scale: high production volume of a component is viable when the same component is used in many product variants and across product lines. This is possible because each component performs a specific function, is physically separable and the interactions with the product are minimized. The economy of scale can draw costs benefits directly to the manufacturer, allowing more efficient production technology in component manufacturing, or indirectly through low cost of a standard component supplied by a vendor.
- Product change: product change can be necessary due to usage throughout the product lifecycle (such as replacement of a worn part) or change to a product over successive generations (driven by changes in customers preferences and/ or technological advances). The existence of modules in a product, with components and interfaces that have different change rates, allow performing changes without affecting the design of the whole product.
- Product variety: product variety plays a central role when deciding to opt for a modular product. Modularity allows combining a smaller set of components to achieve a large variety of end products. This is possible because of the one-to-one mapping of components to the functional elements of the product.
- Flexibility in use: besides allowing the manufacturer to create a large variety of end products, modularity enables users to use the same product in different ways. Either by removing a certain component (such as the seats of a van for cargo space) or by changing components types (such as the lens of a camera).
- Order lead time: in make-to-order situations where the customer is allowed to customize the product, modularization allows the order lead time to be shorter than the lead time to produce the individual components. This is the case when the end product is a combination of different modules or when the product variants are derived from a standard product and the differentiation follows from varying certain components. The modules or standard product and components can be inventoried and then the end product assembled to order.
- Decoupling of tasks: the existence of interfaces between components allow the decoupling of design and of production tasks, which reduces complexity and allow completing tasks in parallel. Likewise, components can be produced and tested separately with a modular architecture.

- Design and production focus: the design and production of components can be more focused and specialized when they are independent. For example, special facilities and work cells can be dedicated to certain components.
- Component verification and testing: due to the unique correspondence between functions and functional elements, testing a specific function should be possible in a modular design. The interface between a component and the rest of the product can, ideally, be simulated, allowing testing the performance of a certain component.
- Differential consumption: modular architecture favours the change of components of the product that have a different usage rate (are consumed faster than the rest of the product) than other components. For example, the blade from razor blades or the bag from vacuum cleaners.
- Ease of product diagnosis, maintenance, and repair: substituting components in a modular architecture allows repairing a product faster than using test instruments to diagnose a specific fault.

The product structure encompasses all product-related information (including documents, CAD models, NC programs, maintenance plans, etc.) and defines the relationship between modules and components of a product (SCHUH, 2005). The product structure is an important resource for managing information in the product lifecycle management (PLM). There is no "one-size-fits-all" reference model for product architecture. Factors related to the development project, such as innovation level and a number of product derivatives, define the best fit. The lifecycle oriented product structuring goes through five phases as identified in Schuh, Assmus and Zancul (2006, p. 2). The first phase, functional specification, translates market demands into product requirements and functions under technologies constraints. The functional specification encompasses assigning product requirements to functions and identifying combination conflicts. Secondly, the identified product functions and requirements are translated into physical modules considering the available technologies and function related costs/ prices. According to functional interdependencies, functions are grouped into modules. The third phase is the definition of modules interfaces based on the functional interdependency between them, which includes the definition and standardization of interfaces. Next, the product program is defined, including planning the complete product range and specifying the variant configuration logic (options and restrictions). Finally, the last phase is the detailing of the product structure to component level and linking all product related information.

3.4 Enterprise Resource Planning Systems

Enterprise Resource Planning (ERP) System is defined as a method to plan and control all resources needed to take, make, ship and account for customers' orders in a manufacturing, distribution or service organization (MADANHIRE, MBOHWA, 2016, p. 225–226). This can be achieved either through internal development or through a software package solution offered by specialized companies. Modern ERP Systems operate over the internet, through cloud services, based on an underlying integrated database, and are responsible for supporting and linking cross-functional processes in an enterprise, storing master and transactional data in a consistent way and with controlled redundancy (ELMONEM, NASR, GEITH, 2016, p. 2; KLAUS, ROSEMANN, GABLE, 2000, p. 143). ERP software is also defined as a package that seeks to integrate a business's processes and functions to present a holistic view of the business from a single information and IT architecture (KLAUS, ROSEMANN, GABLE, 2000, p. 141–142).

Through ERP systems companies are able to integrate internal and external business processes, such as manufacturing, supply chain, sales, finance, human resources, budgeting, and customer services activities (RAJAN, BARAL, 2015, p. 106). Cloud ERP Systems also explore e-commerce capabilities, such as the integration and collaboration with suppliers, partners, customer portals, and tracking of incoming raw materials and outgoing of final products, which extends visibility and control inside and outside the company (ELMONEM, NASR, GEITH, 2016, p. 1–2).

The integration of process allows optimization across the organization, providing a common information technology infrastructure, standardization of processes, faster response to customer requirements, tracking company data and creating common measures (SAATÇIOĞLU, 2009, p. 691). The benefits from the successful implementation of an ERP system are the integration of processes across functional areas with improved workflow, standardization of business practices, and access to real-time up-to-date data (MABERT, SONI, VENKATARAMANAN, 2003, p. 302), higher quality, reduced time to market, improved communications, supporting in decision making, shortened lead times, higher productivity and lower costs (ELMONEM, NASR, GEITH, 2016, p. 1).

ERP software exists in three different levels of configuration (KLAUS, ROSEMANN, GABLE, 2000, p. 142):

- Generic: the most comprehensive form of an ERP system, it targets a range of industries and must be configurated before use;
- Pre-configurated: templates developed from the generic form to serve specific industry sectors or companies of a certain size;
- Installed: the result of configurating generic or pre-configured packages, it is the tailored solution to attend the firm's requirements on site.

Traditional ERP systems can also be categorized into on-premise ERP and hosted ERP (ELMONEM, NASR, GEITH, 2016, p. 2). For on-premise ERP the system runs over the enterprise own infrastructure – servers, network, platforms, computers, etc. In this model, the operation and management of the ERP system follow a software license agreement. Costs related to running the software and maintenance are covered by the company as well as disaster recovery. Hosted ERP follows a service model that encompasses hosting the physical servers and running the ERP system somewhere else outside the plant site through a direct network connection, that may or may not run over the internet (ELMONEM, NASR, GEITH, 2016, p. 2).

The process of software individualisation is called customizing, in order to support its implementation and customization a series of documents and material can be used, such as tools for project management, step by step guidelines, remote checks, presentation files etc. (KLAUS, ROSEMANN, GABLE, 2000, p. 142).

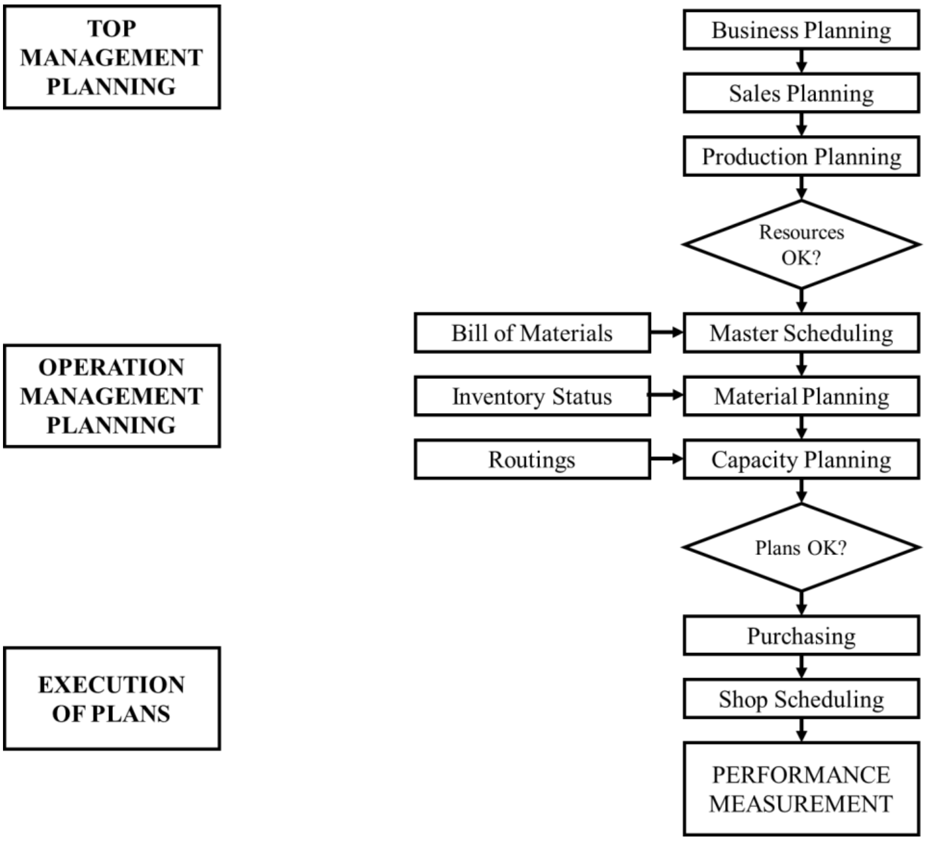
Madanhire and Mbohwa (2016, p. 226) identify seven basic modules usually incorporated in a company:

- ERP production planning module: this module is used for optimizing the utilization of manufacturing capacity, parts, components and material resources. It uses historical data and sales forecast.
- ERP purchasing module: the module provides required raw materials, facilitates supplier management, placing orders and related billing processes.
- ERP inventory control module: responsible for managing stock levels through inventory requirements, monitoring item usage, reporting inventory status, etc.
- ERP sales module: a module used for order placement, order scheduling, shipping and invoicing.
- ERP marketing module: the module supports lead generation, mailing and trends in customer tastes.

- ERP financial module: a module responsible for gathering financial data and generating reports.
- ERP human resources module: module that keeps record of employee data, including contact information, salary details, attendance, performance evaluation and promotion.

The different modules are integrated to allow workflow and information transfer through different parts of the organization. The decision making and order processing is realized by different management levels inside the company. Flowchart 3 shows a standard ERP flow chart. Different levels of the organization are involved in the enterprise resource planning process, here are shown different top-down levels: top management, operations management, and execution of plans (MADANHIRE, MBOHWA, 2016, p. 226).

Flowchart 3 - Standard ERP flowchart



Source: adapted from (MADANHIRE, MBOHWA, 2016, p. 226).

Finney and Corbett (2007, p. 335–338) identify the critical success factors for implementing an ERP system. They categorize the success factors into strategic and tactical critical success factors. The first being those addressing the whole implementation and an overall view involving the breakdown of goals into smaller tasks, and the second as those involving skills and methods for achieving the defined objectives. Table 3 summarizes and separates the critical success factors identified by the authors.

Table 3 - Critical success factors for ERP implementation

Strategic critical success factors	**Tactical critical success factors**
Top management commitment and support	Balanced team
Visioning and planning	Project team
Build a business case	Communication plan
Project champion	Empowered decision makers
Implementation strategy and timeframe	Team morale and motivation
Vanilla ERP	Project cost planning and management
Project management	BPR and software configuration
Change management	Legacy system consideration
Managing cultural change	IT Infrastructure
	Client consultation
	Selection of ERP
	Consultant selection and relationship
	Training and job redesign
	Troubleshooting/ crisis management
	Data conversion and integrity
	System testing
	Post-implementation evaluation

Source: (FINNEY, CORBETT, 2007, p. 335).

The critical success factors are explained in the sequence based on definitions provided by Finney and Corbett (2007, p. 335–339):

- Top management commitment and support: due to the high impact of an ERP implementation in a firm, having a committed top management – that is technically orientated and capable of anticipating implementation problems and solving them – is decisive for successfully implementing the new system.
- Visioning and planning: refer to the identification of clear goals and objectives, and establishing a clear link between the business goals and the system implementation.

- Build a business case: justifying the implementation of the ERP system with economic and strategic reasons before starting the ERP system implementation.
- Project champion is the focal point of the project, this person should have strong leadership skills, business and technical competencies.
- Implementation strategy and timeframe: the implementation strategy should be defined together with its phases and under a planned time frame.
- Vanilla ERP: is a suggestion found in the literature for companies implementing first a basic version (with no or minimal customization) before implementing a more robust version. Project management for managing and carrying out the implementation plan, which includes planning the stages, allocating responsibilities, defining milestones and critical paths, training and human resource planning, and determining the success measures.
- Change management: one of the most cited critical success factors. Change management is the anticipation and preparation of the company for the implementation and use of the ERP system, particularly user acceptance.
- Managing cultural change: part of the change management, and relates to minimizing the adoption costs of all stakeholders involved as much as possible and securing the change of culture for using the new system.
- Balanced team: the need for an implementation team that represents different parts from the organization (from the business as well from the IT side) and that, therefore, possess the required skills for implementing the new system. The same idea applies to project team, reinforcing the need for an implementation team with people acknowledged as the best suited for the task. This, although, does not mean there will not be the need for training the individuals for using the system after the implementation is concluded.
- Communication plan: refers to communication between the different levels of the organization, between business and IT personnel and also between shop-floor employees.
- Empowered decision makers: relate to the need of having people empowered enough and able to make the necessary changes throughout the ERP system implementation, specially to ensure the effective timing of the project.
- Team morale and motivation: necessary to carry out the project, it is under the responsibility of the team leader/ champion of the implementation project.
- Project cost planning and management: reinforce the need of calculating and knowing in advance the costs of implementing the ERP system, however, it is also possible that

unexpected costs arrive during the implementation process. Therefore, it is also necessary to anticipate and prepare for additional costs.

- BPR and software configuration: BPR stands for Business Process Reengineering and refers to a complete description of how the business will operate after the package is installed and configurated. This is in order to match the requirements to the implemented software.
- Legacy system considerations: directly affect the implementation of the ERP system and its future use, it can help to indicate the nature and scale of potential problems.
- IT infrastructure and IT readiness: critical for implementing the new system, the architecture and skills of the organization should be assessed in order to determine if they have to be upgraded or revamped before starting the implementation process.
- Client consultation: refers to the necessity of communication and consultation with project's stakeholders, particularly with the client, in order to avoid misconceptions.
- Selection of ERP: the selection of the ERP package to be implemented in the company. The system should be able to serve the organization by matching its business processes.
- Consultant selection and relationship: the relationship with the ERP consultant is important in order to guarantee proper knowledge transfer from the consultant to the company and reduce the dependency on the vendor/ consultant.
- Training and job design: training of company personnel to use the new system is highly important for securing implementation and usage success. It might also be necessary the development of IT skills in order to sustain the system. With the changes implemented through the ERP system, it might also be necessary to redesign the role and responsibilities of company personnel.
- Troubleshooting and crisis management: refers to the needed flexibility to prepare to handle unexpected problems throughout the implementation process.
- Data conversion and integrity: in case the implementation of the ERP system requires the conversion of existing data in the firm, it is important to secure that the data integrity is being preserved and that suspect data is being cleaned from the system.
- System testing: on the final stages of the implementation process, through testing and simulation exercises, is important to be done before the system goes live in order to make corrections and adjustments.
- Post-implementation evaluation: the feedback given after the implementation is complete. Maintaining a feedback network and continued management support is also important for continuous system improvement.

ERP systems are being challenged by changes brought by the fourth industrial revolution. Maintenance for instance is key for the factory of the future. Some ERP system providers have addressed this issue by adding functionalities for predictive maintenance, integrating diagnostic and prognostic models of equipment wear (HADDARA, ELRAGAL, 2015, p. 723). Another matter is the horizontal integration, between different organizations, that requires ERP systems to integrate fully with Supply Chain Management systems. This integration is important to protect against counterfeiting and to ensure the correct utilization of raw materials and products (HADDARA, ELRAGAL, 2015, p. 723). Cyber-Physical Systems also require a robust communication network between machines, humans, processes and products to exchange real-time data. Haddara and Elragal (2015, p. 728) conclude that, although ERP systems are technologically and operationally ready to support the factory of the future, the lack of a unified standard and protocol between machines and ERP systems is still a barrier for its further implementation.

4. Results

This section presents the achieved results. The first subsection begins with the specialist interview, complementing the literature review. The skateboard’s parameters are then defined. The skateboard’s product architecture and the definition of which parts/ components have an identification number is presented next. The second subsection shows the results from the ERP system implementation, including the product configurator and the integration with the Manufacturing Execution System (MES).

4.1 Configuration Parameters Definition

Complementing the literature review performed in section three and in order to enrich the understanding of the product to be produced at the learning factory “Fábrica do Futuro USP", the results section begins by presenting the specialist input obtained through an interview that occurred on the third of April 2019.

The interviewee is the owner of a skateboard store. The retail store is a Brazilian company located in São Paulo, that currently sells skateboards and clothing. The store outsources the production of skateboards to two factories, both located in Brazil. The skateboards production, even in the specialized industry, is highly handcrafted and not automated.

The store clients are divided into two main categories: athletes and amateurs. They practice mainly three modalities of skating: street, vertical and bowl banks/ parks.

According to the interviewee, the main variables chosen by a consumer to personalize the skateboard and thus defining its style are summarized in Table 4.

Table 4 - Variables and parameters according to specialist - continues

Variable	**Parameter**
Deck dimension	▪ width
	▪ thickness
Material	▪ ivory with fiberglass
	▪ wood (maple)
Wheels	▪ size
	▪ hardness
	▪ colour

Source: author’s own production.

Table 5 - Variables and parameters according to specialist - conclusion

Variable	**Parameter**
Truck	▪ size ▪ torque adjustable according to the other variables – tested at the time of purchase
Sticker/ print	usually already printed on the skateboard from the factory (using heat transfer). Consumers are becoming more demanding some level of personalization is already possible for larger batches

Source: author's own production.

The variables contemplated by the skateboard produced in the FF are somewhat different from those chosen in a real purchase situation. Besides the aforementioned variables, the production in the learning factory offers the possibility of adding the connectivity box and the rails, that were presented in section one. Table 6 presents the variables and parameters adopted at the LF.

Table 6 - Variables and parameters of the skateboard produced at the LF

Variable	Parameters
Dimension	fixed – only one deck currently available
Material	fixed – only one type of wood currently available
Wheels	▪ size: fixed ▪ hardness: fixed ▪ colour: 4 variants, different positions
Truck	▪ size: fixed ▪ torque: adjustable, range of possibilities
Sticker/ print	fixed – currently the only sticker option is the logo from the FF
Connectivity box	optional – either selected or not by the customer
Rails	optional – either selected or not by the customer

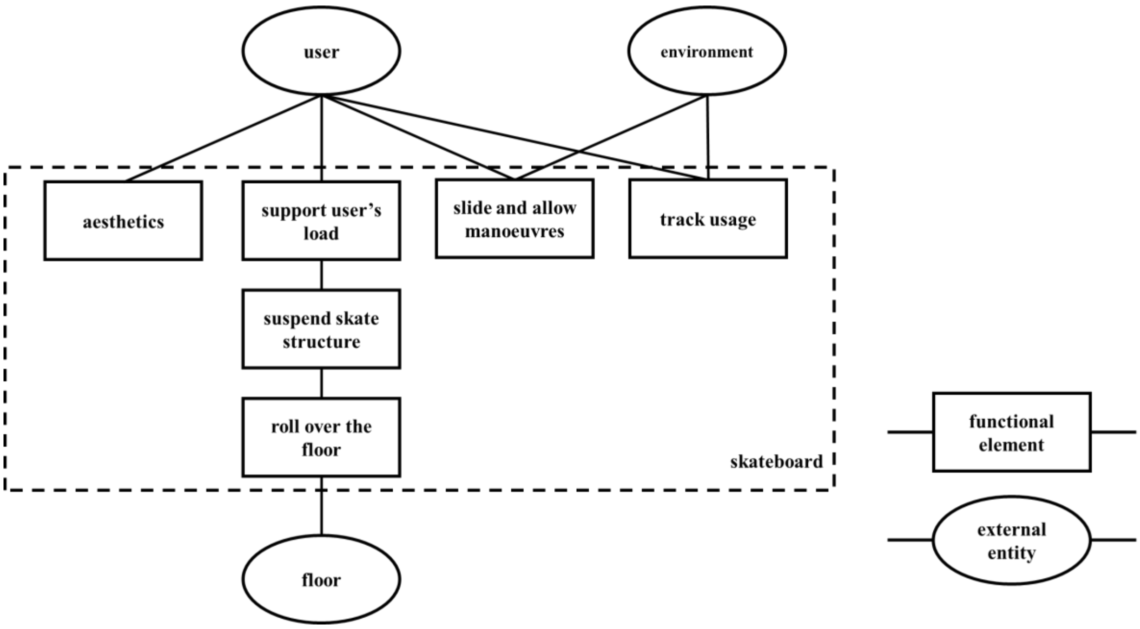
Source: author's own production.

Some differences exist between the skateboard produced in the FF and a real purchase situation. These differences (such as the variety of deck's material, deck and wheel size, etc.) exist due to practical and cost reasons. The specialist input and the understanding of a real skateboard production is, therefore, important for making both processes as similar as possible. The differences as mentioned earlier can be eventually changed and new options may be added to the assembly process in the future.

4.1.1 Product Architecture

Based on the definition presented in the third section, Figure 13 presents the function structure for the skateboard produced at the FF. The skateboard interacts with the user – by supporting the user's load with the deck, truck and wheels –, with the floor (or any surface that it is standing on) through the wheels and with the environment through the connectivity box that tracks the skateboard location and the rails that allow the skater to perform manoeuvres in different surfaces.

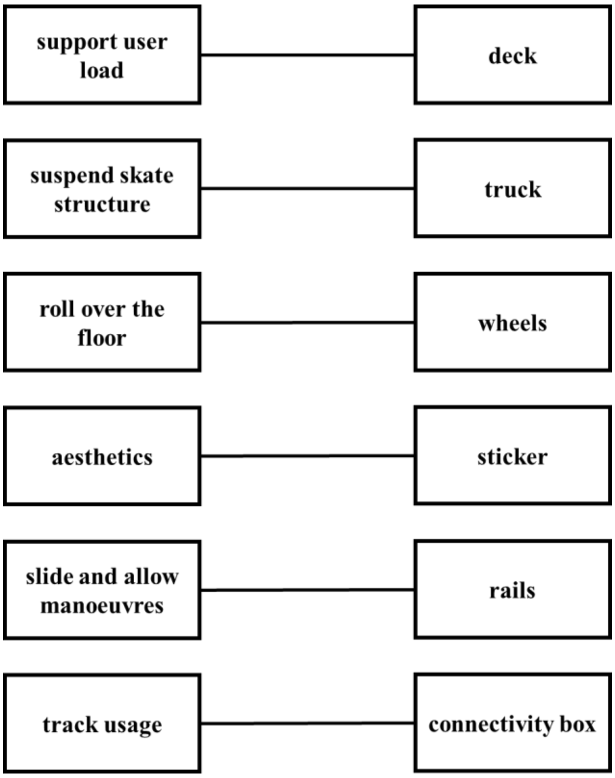
Figure 13 - Skateboard function structure



Source: author's own production.

The definition of the functional elements and their connection to external entities allowed doing the mapping of functional elements to the skateboard's physical components. As shown in Flowchart 4, the skateboard has a one-to-one mapping of functional elements to physical components – not taking into account fasteners – which allows for a modular product architecture.

Flowchart 4 - Mapping of functional elements to physical components



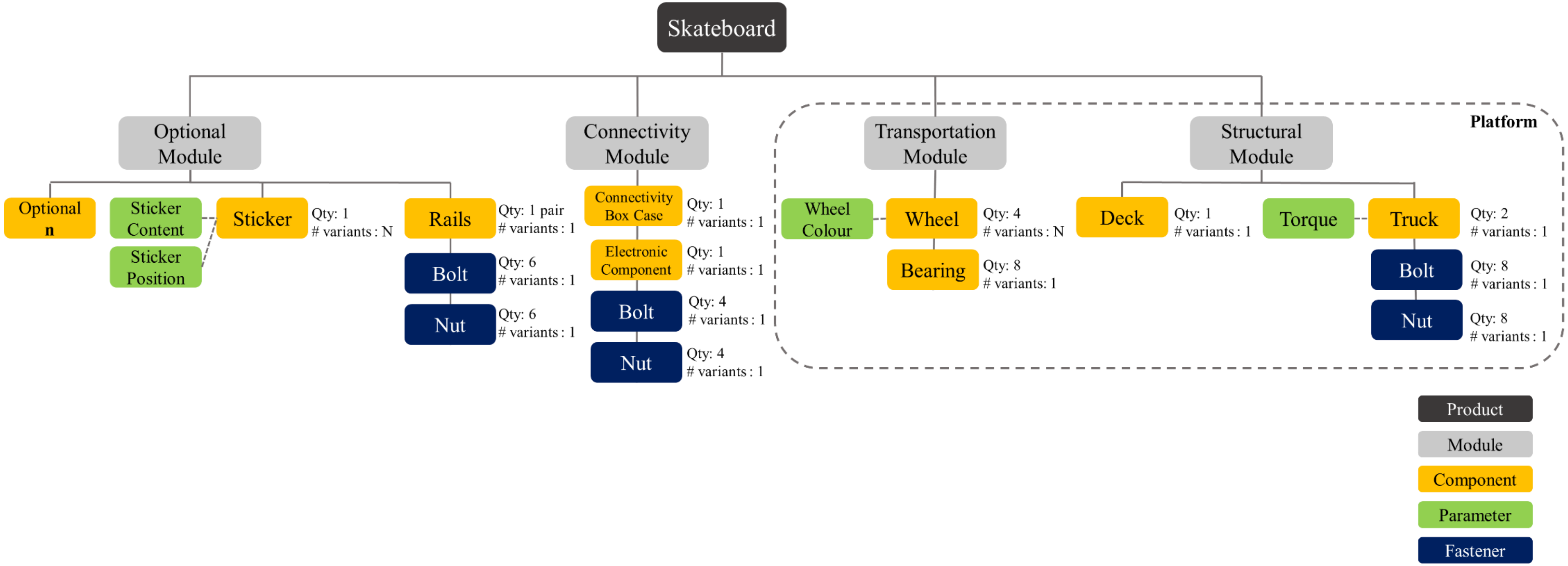
Source: author’s own production.

Based on the mapping of functional elements to the physical components the product architecture presented in Flowchart 5 was defined.

The skateboard assembled at the FF has two modules that are common to all finished product: the structural module and the transportation module. The structural module has a deck, two trucks and the necessary fasteners. The transportation module includes four wheels and four bearings. Both these modules constitute the product platform, here understood as the part of the product that is present is all finished products.

The connectivity and the optional modules can be included or not in the finished product according to the consumer’s choice. The connectivity module consists of a connectivity box case, a set of electronic components and fasteners. The optional module has, for now, only the rails, with its fasteners, and the sticker. In the future, it is possible and desirable to expand the optional list and add new features to the skateboard.

Flowchart 5 - Product architecture



Source: author's own production.

Besides defining the skateboard's architecture, it is also necessary to define which parts or items from the product structure are to be numbered, how this number (or identification code) is determined and when it should be changed.

According to Garwood (1995) there must be an identification number to every item that:

I. was bought or manufactured and that has to be programmed, in order to satisfy the identified needs in the sales forecast or in the orders backlog;
II. the stock or production flow need to be controlled;
III. is sold in the spare parts market;
IV. is reworked, substituted or eliminated in remanufactured products.

Table 7 presents the decision table used to analyse every part used for assembling the skateboard. The four criteria previously presented are evaluated in each column, and the parts are evaluated in each row of the table.

Table 7 - Part number decision table

Item	**I.**	**II.**	**III.**	**IV.**	**Decision**
Deck	✔	✔	✖	✖	Assign number
Truck	✔	✔	✖	✖	Assign number
Wheels	✔	✔	✔	✖	Assign number
Bearing	✔	✔	✔	✖	Assign number
Connectivity box	✔	✔	✖	✔	Assign number
Rails	✔	✔	✖	✔	Assign number
Sticker	✖	✖	✖	✖	Do not assign number
Bolt	✖	✖	✖	✖	Do not assign number
Nut	✖	✖	✖	✖	Do not assign number

Source: author's own production. ✔ = applies, ✖ = does not apply

The deck is bought from a supplier, currently there are 10 decks available at the learning factory. The demonstration of the assembly line will use the decks sequentially. Assigning a number to each deck allows differentiating the date each batch was ordered and rotating their usage, thus ensuring that the wear of decks is evenly distributed.

The trucks currently available at the FF were bought from a supplier, in the future some of the trucks will also be manufactured at the manufacturing site, simulating production in two different plants. The part number will not only allow controlling the produced parts, but also controlling for deterioration of usage (similarly to the decks).

Wheels and bearings are important components of the transportation module. Their stock and replenishment should be controlled. These parts should, therefore, have identification numbers.

Bolts and nuts (fasteners) were bought in large quantities and thus do not have to be as strictly controlled as the items mentioned above.

The connectivity box and the rails are 3D-printed in the FF and result from the work of students involved in the implementation of the LF. Numbering these items allow not only controlling the production, but also keeping track of the performance and usage of each component, that are not as simple as products purchased from suppliers.

Stickers do not have to be numbered or identified due to their perishable nature and to fact that they are customized and printed for each customer.

Because the skateboard produced at the FF are disassembled and their components are reused in new production simulations, the decision to change parts/ products identification numbers were also taken into account. Two items have different part numbers when they are not interchangeable. An item is interchangeable when it fulfils simultaneously two prerequisites (CLEMENT, COLDRICK, SARI, 1992):

- has functional and physical (material, shape and dimensions) characteristics equivalent in performance, reliability and maintenance to another item that has a similar or identical purpose;
- is capable of being exchanged for another item without alterations in other items from the product, except in terms of adjustments and calibrations.

Therefore, an item part number only has to be changed when its interchangeability is affected. This results in a change of each skateboard identification generated by a different customer, and the preservation of components numbers as long as they are not worn out.

4.2 Enterprise Resource Planning System

The ERP system is being implemented at FF by TOTVS, an Information Technology (IT) Brazilian firm which is one of the partners from the Fábrica do Futuro USP. TOTVS is a software-based enterprise. Its products range from ERP systems, Business Intelligence, Customer Relationship Management, Human Resources, and e-Commerce solutions, among others.

The company offers specialized solutions for manufacturing firms. The software package includes modules for supporting the following activities (TOTVS, 2019):

- Product life cycle management: engineering, product development, product configurator and project management;
- Sales: sales orders, price list, sales quotation, sales contracts, sales portal, customer relationship management;
- Procurement: purchasing, purchasing contracts, inbound delivery, purchase planning, quality control, online quotation and supplier search;
- Planning: sales forecast, master plan, material planning, capacity planning, industrial production management;
- Inventory: inventory management, invoice control and management, warehouse management, Radio Frequency Identification (RFID), inventory optimization, data collection;
- Production: production control, shop floor control, industrial costs, advanced manufacturing, e-Kanban;
- Logistics: billing, distribution management, shipper freight management, logistics optimizer, import and export, stock balancing;
- Maintenance: maintenance of assets, metrology, fleet maintenance, after-sales, technical assistance.

The company has three ERP solutions for manufacturing firms: Protheus, Datasul, and Logix. Datasul is the one chosen to be implemented in the FF.

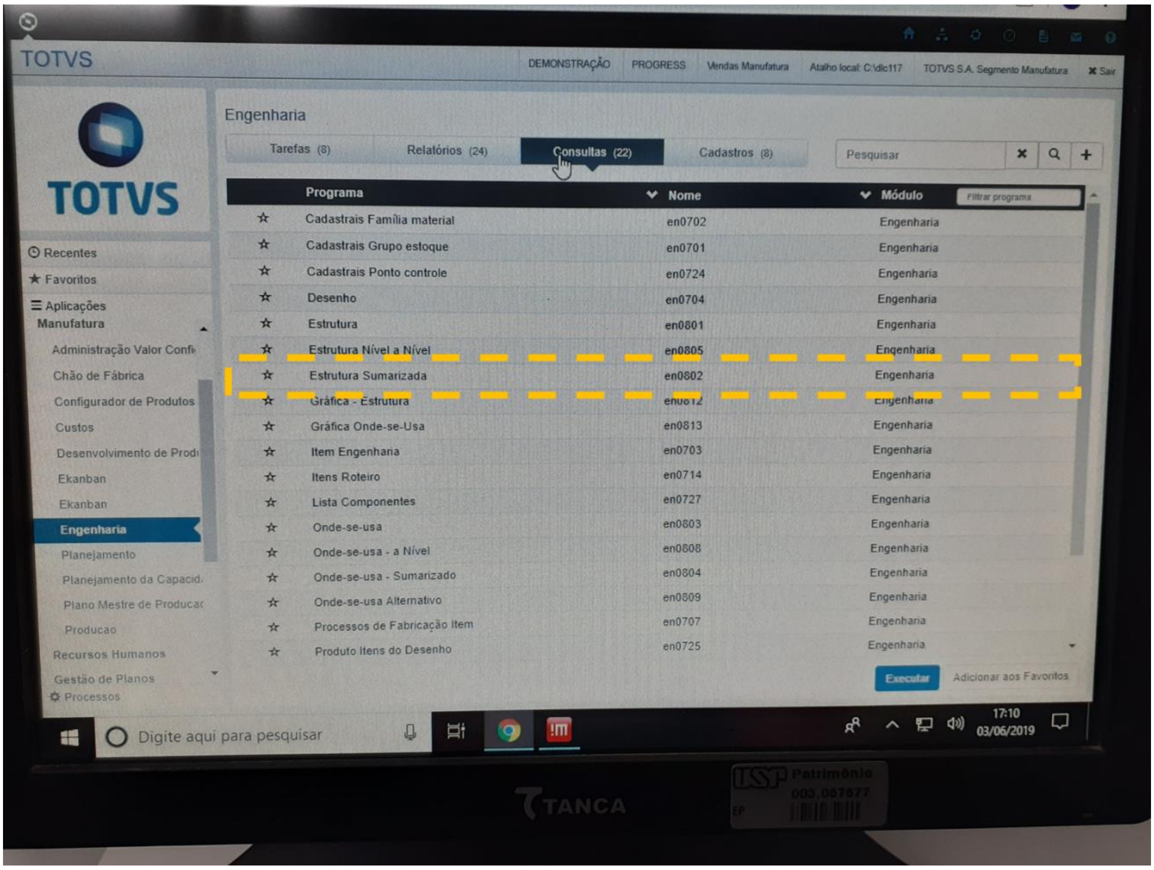
Following what is suggested in the literature, the first phase of the ERP implementation does not include all modules and resources from Datasul that will be used in the FF. The first phase, thus, is focused on the basic modules and functions of the ERP system to support production management. Moreover, a relevant requirement included was to allow product customization. Therefore, a configurator has been included in the first implementation phase.

The engineering module was customized and installed in USP's servers. The customization started with the registration of the product architecture.

Division through “ghost” items and non-ghost items. Ghost items are the product modules and non-ghost items are the components.

Ghost items are not assigned to the production order, and do not count for inventory control. In case the structure is prepared for semi-finished goods (e.g. the part of the product that is common to all products), ghost items can be turned into non-ghost items and the system is capable of tracking their production as well. The product architecture can be retrieved from the system through the item “en0802” in the engineering module’s consultation tab, as shown in Photograph 3.

Photograph 3 - Consultation tab - product architecture

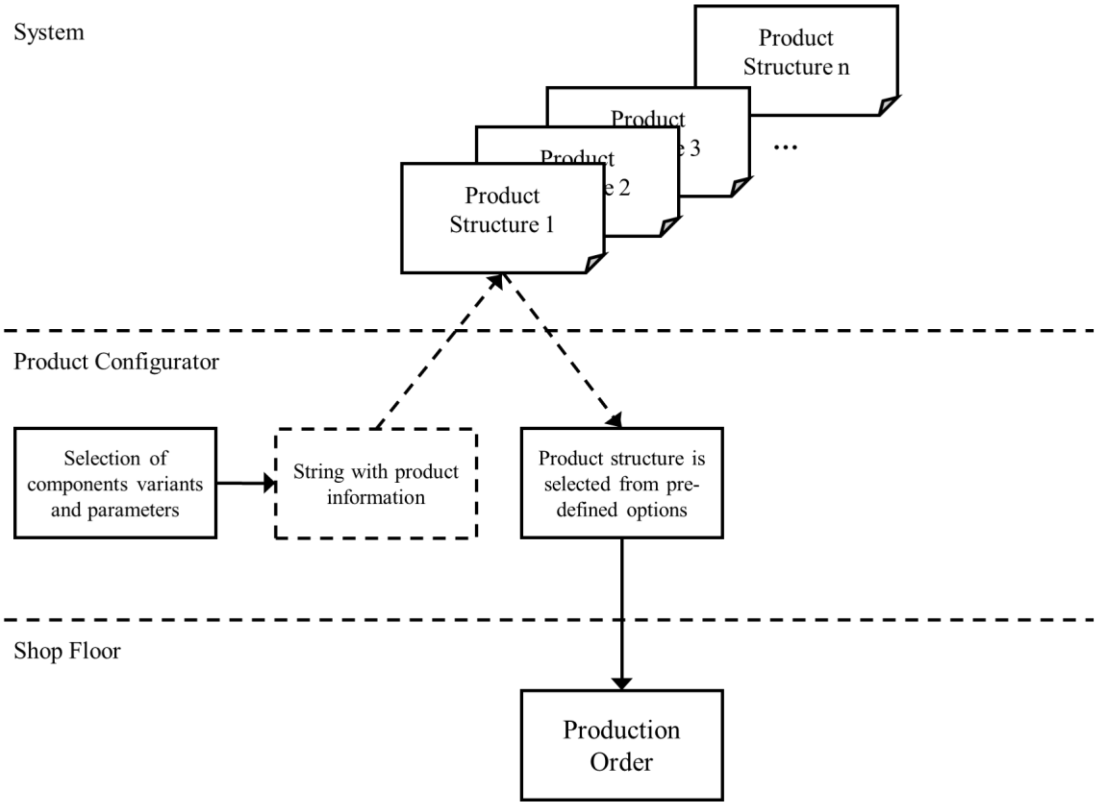


Source: author’s own production.

The product architecture is the input for generating production orders, setting up the product configurator and controlling for inventory levels.

Particularly important for this work is the process of turning sales order in the ERP into production orders in the Manufacturing Execution System (MES), the software responsible for the shop floor management. The process by which customer’s specifications are turned into a production order is particularly important for the ERP system architecture. The process currently implemented at the FF is presented in Flowchart 6. In this model, there are pre-defined product structures (all possible combinations of components variants and parameters) registered in the system. In this case, the product configurator is solely responsible for converting the consumer's input into a code that links this selection to a pre-defined product structure. The pre-defined product structure generates the production order that is sent to the MES.

Flowchart 6 - Production order generation process I

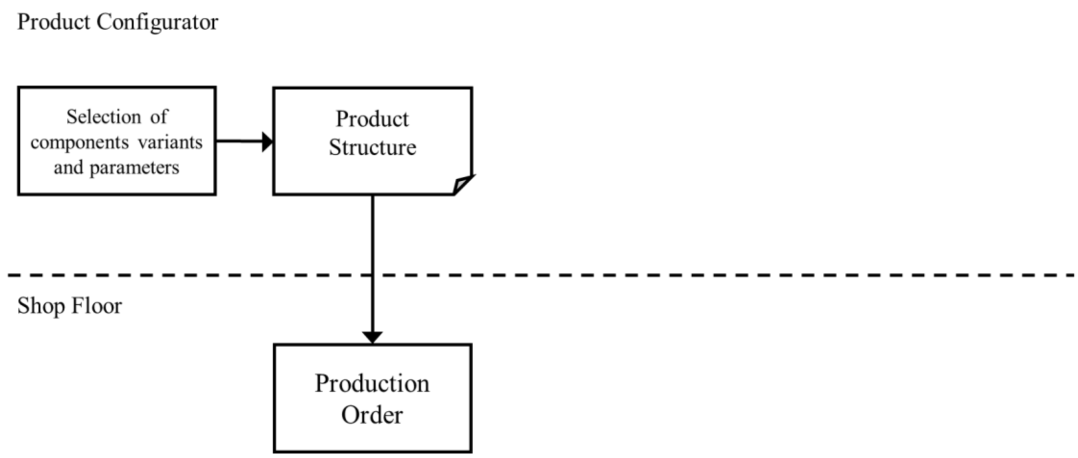


Source: author's own production.

This process for generating production orders from customer's input has the benefit of being easy to implement (because the product configurator does not have to create a new product structure for each customer order and thus can be less complex). However, this system architecture is not sustainable when the amount of product variant is too large. The amount of combinations grows exponentially and registering each new combination is not practical for system administrators.

The other option for generating production orders through the customer's input is shown in Flowchart 7. In this model each customer selection of components and variants generates a new product structure. The product structure generates then the production order in the MES. This allows a flexible customization environment that does not require large maintenance for each update in product architecture.

Flowchart 7 - Production order generation process II



Source: author’s own production.

This second architecture alternative is also supported by the ERP system and its implementation is planned for in a second phase (not concurrently to the time this work was developed).

4.2.1 Product Configurator

The product configurator inside the engineering module developed by TOTVS is based on the product architecture described in section 4.1 Product architecture.

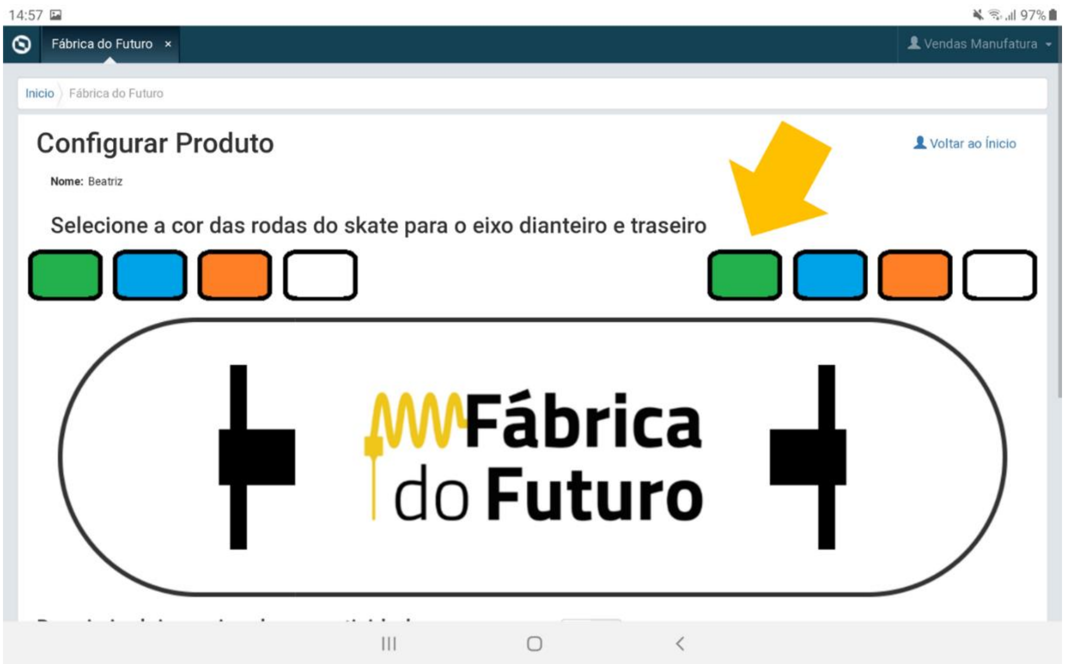
The initial page of the product configurator is presented in Photograph 4. In the initial page the system asks for the customer’s name in order to start the customization process.

Photograph 4 - Product configurator - initial page

Source: author’s own production.

The customization page displays a graphic representation of the skateboard. Photograph 5 shows the first part of the customization page, in this part the customer selects the colours of the front and back wheels by clicking in one of the coloured shapes displayed above the skateboard (indicated by the yellow arrow in the figure).

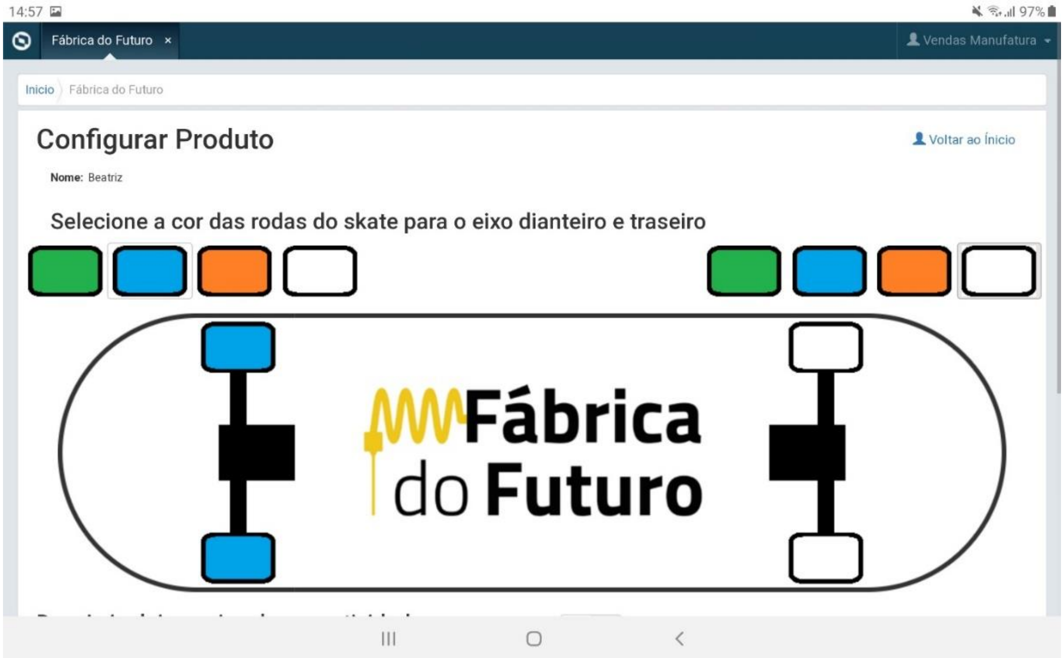
Photograph 5 - Product configurator - customization page 1/6



Source: author’s own production.

The wheels of the selected colours appear in the skateboard as shown in Photograph 6. The wheels' colours are chosen in pairs (same colour for both wheels on the front and same colour for both wheels on the back).

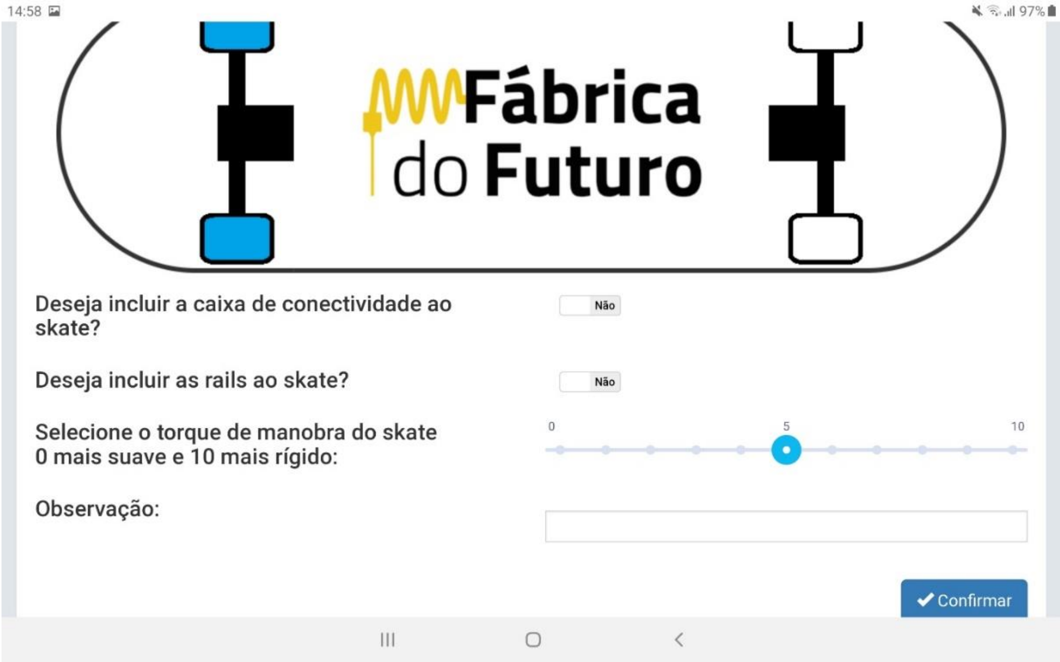
Photograph 6 - Product configurator - customization page 2/6



Source: author's own production.

The second part of the customization page allows the customer selecting if he/ she wants to add the connectivity box to the skateboard (yes/ no decision), if he/ she wants to add the pair of rails (yes/ no decision), and which torque he/she wants to apply to the trucks. It is also possible to add an observation by the end of the customization process, as seen in Photograph 7.

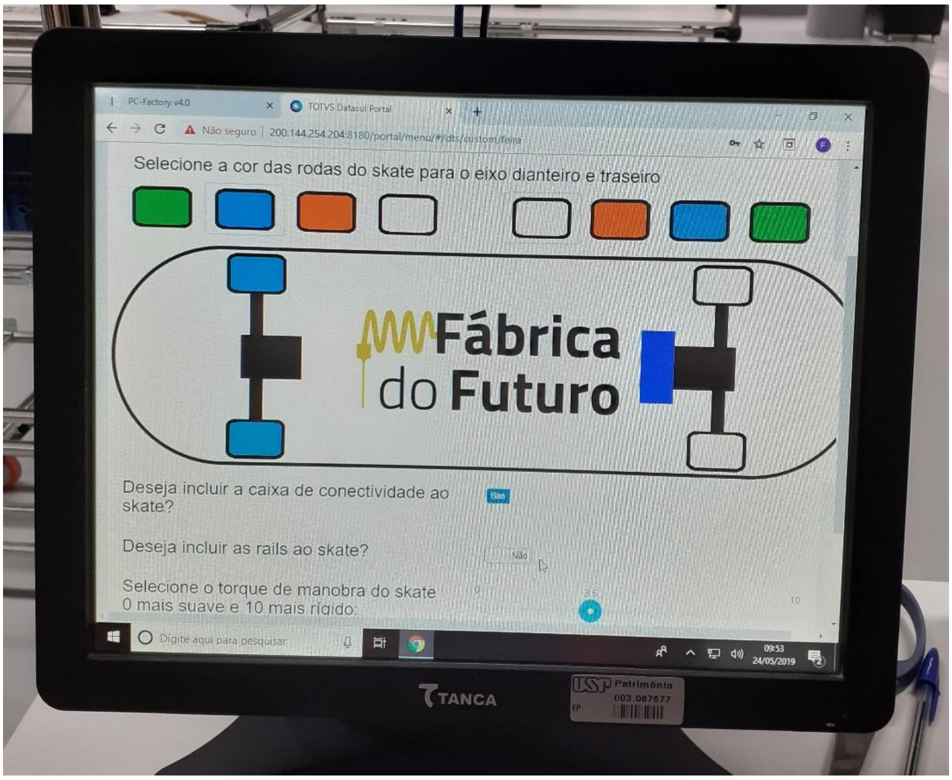
Photograph 7 - Product configurator - customization page 3/6



Source: author's own production.

Photograph 8 shows the change in the skateboard graphic representation when the customer chooses to include the connectivity box.

Photograph 8 - Product configurator - customization page 4/6



Source: author's own production.

Photograph 9 shows the change in the skateboard drawing when both the connectivity box and the rails are chosen by the customer. Both additional features are displayed at the approximate position on the skateboard.

Photograph 9 - Product configuration - customization page 5/6

Source: author’s own production.

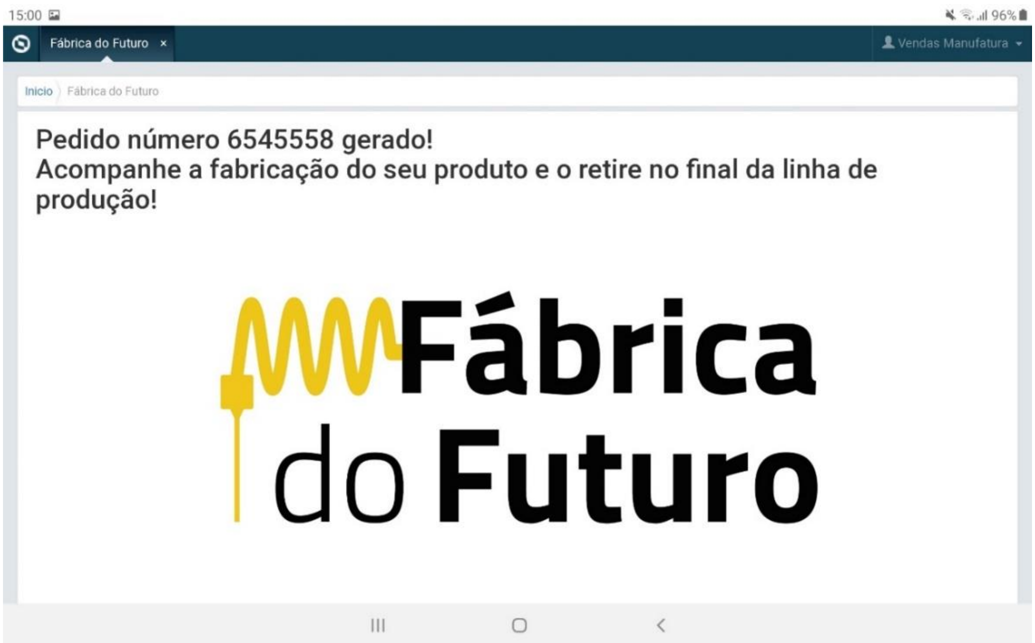
Photograph 10 shows the customer choosing the torque applied to the skateboard’s truck. The torque intensity can be selected from a set of options ranging from the most loose to the tightest torque.

Photograph 10 - Product configurator - customization page 6/6

Source: author’s own production.

Finally, Photograph 11 shows the final page of the configurator, which indicates that the order was created, also informing the identification number of the product.

Photograph 11 - Product configurator - final page



Source: author’s own production.

The product configurator was used in a presentation of the FF on the 6th of April 2019. Its performance and integration with the MES system worked perfectly.

4.2.2 MES Integration

The Manufacturing Execution System (MES) is being implemented by the partner company PPI Multitask, using the software PCFactory (also installed in USP's servers). Since the focus of this work is not on the MES implementation, only an overview highlighting the integration between the ERP system and the MES is presented.

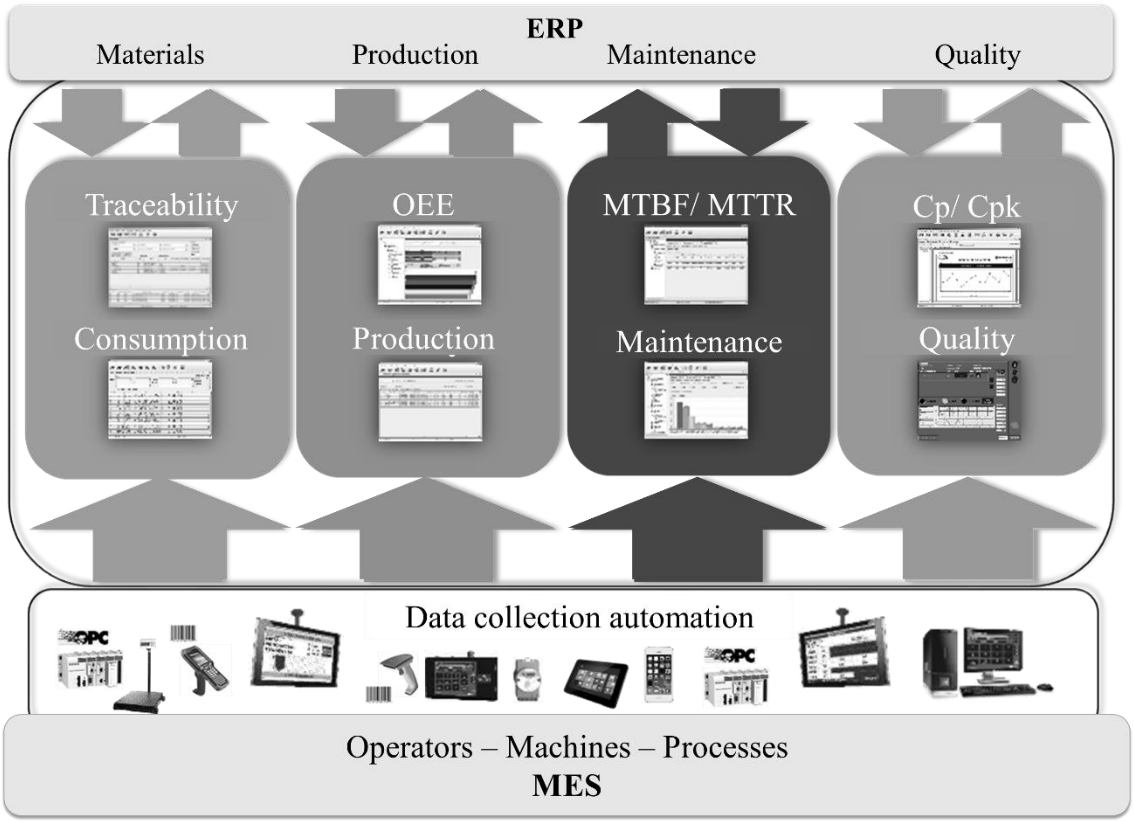
According to Kletti (2007, p. 14) the functional scope of a MES is:

- Production: production data acquisition, manufacturing development engineering, distributed numerical control, control station;
- Personnel: staff work time logging, access control, short-term manpower planning;
- Quality assurance: centre for audit quality, measured data acquisition.

MES data acquisition and evaluation systems are done in a common network and exchanged with the ERP system. MES is also responsible for short-term controls, when correction decisions are required to be made fast and as a function of available resources (KLETTI, 2007, p. 16).

Figure 14 shows the different aspects of the ERP system and MES integration. The MES provides, therefore, materials, production, maintenance and quality consolidated data from the shop floor management level to the ERP system. The data exchange happens through a common network connected through USP's servers.

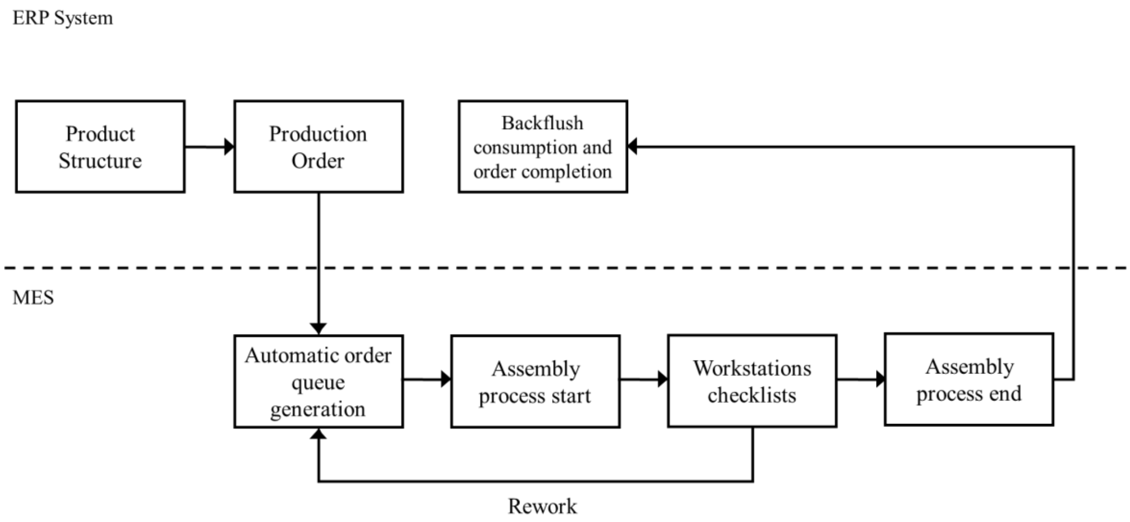
Figure 14 - ERP and MES integration



Source: adapted from presentation slides provided by TOTVS. OEE = Overall Equipment Effectiveness; MTBF = Mean Time Between Failures; MTTR = Mean Time to Repair; Cp/Cpk = capability index.

Flowchart 8 show the sequence of data exchange between both systems. Starting in the ERP system with the product structure specified by the consumer, the production order is generated and transmitted to the MES. The MES generates automatically the queue order (using the First-in-First-Out rule). The assembly process starts by selecting the first production order at the first work station, and continues by the worker's indication of each completed task in the workstation's checklist. The assembly process ends when the last "box" of the checklist is done. The information of order completion is sent to the ERP system, closing the loop. In case rework is needed, this information can also be inserted in the MES and one or more stations can be repeated.

Flowchart 8 - ERP and MES integration



Source: author’s own production.

5. Conclusion and Next Steps

The present work is inserted in the context of the learning factory “Fábrica do Futuro USP” implementation. The learning factory in question is focused on demonstrating Industry 4.0 solutions for the production of the future. This work’s main contributions are the skateboard product architecture definition and the assistance and testing of the Enterprise Resource Planning system implementation.

Learning factories are important learning environments, as they support the learning process with hands-on activities that enhance the learning curve of (future) industry personnel (TISCH et al., 2016, p. 1356). The FF model product is a skateboard, which has a deck, truck, wheels and bearings as key components, and the connectivity box and rails as optional components. The skateboard assembled at the FF presents a certain degree of customization, thus illustrating the lot-size-one emerging tendency in industry.

The literature review elucidated the main topics linked to the product architecture development and implementation. Beginning with Industry 4.0 and its main drivers, the concept of CPS pose an interesting opportunity for its application in the LF. The three levels of a CPS (services, cloud computing and physical objects) work together to create a connected and smart production environment, with real-time data collection and analysis and automatic system response to changes (DRATH, HORCH, 2014, p. 57). An initial implementation of a CPS is already in progress, through the connectivity box developed by the CITI-USP coupled to the skateboard.

The emerging trend of mass customization, producing a high degree of product variants keeping near mass production efficiency (DA SILVEIRA, BORENSTEIN, FOGLIATTO, 2001, p. 1), is enabled by industry 4.0 flexible manufacturing environments. FF’s production system fits into the Customized Assembly category identified by Forza and Salvador (2006, p. 10), as customers’ requirements are taken into account before the assembly process, but do not have influence over components fabrication.

It is also understood that a large amount of product variants does not necessarily yields market success. Providing the right number of variants in the right way (using visual resources, offering information about the product, guiding the customer through the purchasing process, etc.) is crucial for overcoming the so-called “paradox of variety” and fully benefiting from product customization (HUFFMAN, KAHN, 1998, p. 492). And for that product configurators have an important role. Product configurators are information systems that aid customer selecting the specification of the product configuration besides the creation and management of configuration knowledge (KRISTJANSDOTTIR et al., 2018, p. 196). They bring benefits such as significant lead time and man-hour reductions in quotation- and production preparation-related processes (HVAM et al., 2013, p. 336), improved quality of product specifications, lower the risk of strategic competence lost due to the departure of a key sales employee (FORZA, SALVADOR, 2002, p. 98), quality improvements (such as the reduction of assembly errors) (HVAM, 2006, p. 424), and the improvement of product-related and experience-related benefits perceived by customers (TRENTIN, PERIN, FORZA, 2013, p. 442).

IT-related and knowledge acquisition challenges identified by Kristjansdottir et al. (2018, p. 199) were surpassed by partnering with a specialized ERP provider, that also designed an integrated product configurator. Product-related challenges were resolved by developing a modular product architecture previous to system implementation.

Product modularity presents many advantages when compared to traditional architectures. These include components economies of scale, ease of product change, greater product variety, greater flexibility in product use, smaller orders lead time, decoupling of tasks, design and production focus of individual components, independent component verification and testing, differential consumption of components and parts (ULRICH, 1994, p. 223–225). The skateboard's product architecture was developed based on the examples from Ulrich (1995, p. 421). The modular architecture is divided into four modules: structural module, transportation module, connectivity module and optional module. The structural module is composed of a deck and two trucks, plus fasteners. The transportation module has four wheels and eight bearings, besides the necessary fasteners. The connectivity module, responsible for tracking the skateboard use and creating its digital twin, is composed by a connectivity box case and the electronic components. Finally, the optional module currently has a pair of rails and the sticker. Future work on the product architecture can expand the list of optional components and explore other customization concepts, such as the sticker personalization.

The modular product architecture served as initial input for the ERP system configuration. The ERP system implementation is being carried out by TOTVS, a Brazilian software company and a close partner from the FF. Through weekly meetings, system testing and feedbacks, an operating version of the product configurator was successfully implemented. Also, the ERP system integration with the MES, provided by the partner company PPIMultitask, enables customer orders generation, assembly process monitoring and registering the consequent process data.

There is still great potential for future work in the FF. Future research may focus on expanding the customization level of the model product, and for that, it is recommended to update the order generating process for the second and more flexible version presented in Flowchart 7.

Integrating other technologies to the assembly process, such as RFID tags, are already on the development pipeline and can benefit from the parts numbering decisions suggested in section 4.1.1 Product Architecture.

Further understanding of CPS and digital twin architectures are needed to implement this concept in the FF. Expanding the current work of the connected skateboard to the entire assembly process.

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APPENDIX A – Product architecture banner

ARQUITETURA DO PRODUTO
PRODUTO CUSTOMIZADO

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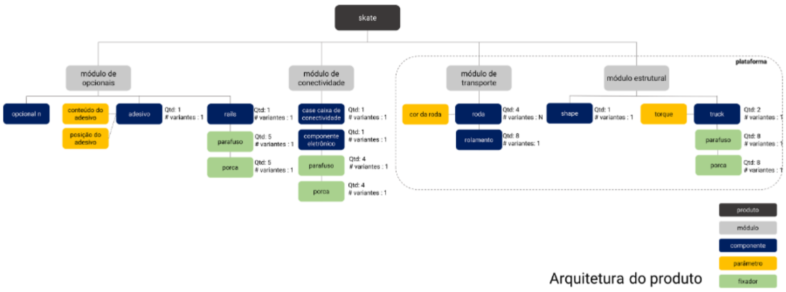
Arquitetura do Produto
A arquitetura de produto é o esquema visual que liga as funções do produto aos seus componentes físicos e às especificações de interface (ULRICH, 1995).

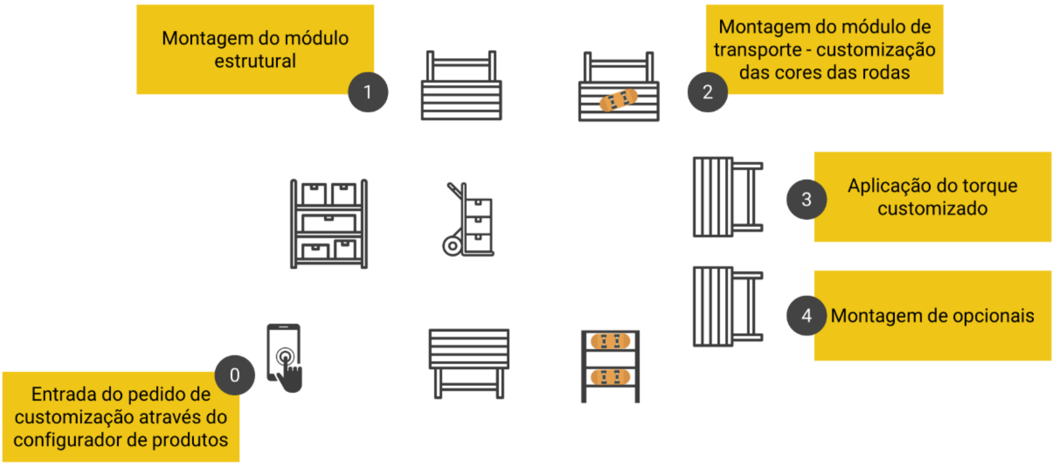
Skate



Arquitetura do produto

Produto Customizado
Um produto é customizado quando uma ou mais de suas atividades operacionais de produção (design, fabricação, montagem e distribuição) são realizadas com base nos requisitos expressos pelo cliente (FORZA, SALVADOR, 2006).

Configurador de Produtos
Os configuradores de produtos são sistemas de informação que ajudam o cliente a selecionar a especificação da configuração do produto, além da criação e gerenciamento do conhecimento de configuração (KRISTJANSDOTTIR et al., 2018).



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