Factory Design of the Learning Factory "Fábrica do Futuro"

Capstone Project I
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Abstract

This work focuses on creating the first iteration of the learning factory *Fábrica do Futuro* of the University of Sao Paulo. To achieve this, an assembly line for skateboards is planned, designed, optimized and implemented, including factory layout and internal processes. Muther's systematic layout planning (SLP) is utilized in combination with time and motion studies to define and optimize the first assembly line of the learning factory.

The goal is to create the foundation for a state-of-the-art learning factory in term of industry 4.0 and logistics 4.0 to connect industry and university research and foster effective cooperation.

Lastly, innovative technologies in the sense of logistics 4.0 are analyzed and provided as implementation opportunities into the learning factory in its road to a state-of-the-art facility.

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List of Abreviations

AGV	Automated Guided Vehicle
API	Application programming interfaces
AR	Augmented Reality
BOM	Bill of material
CPS	Cyber-physical systems
IoT	Internet of Things
P-Q Chart	Product - Quantity Chart
SLP	Systematic Layout Planning
UAV	Unmanned Aerial Vehicles
VR	Virtual Reality

1 Introduction

This work focuses on the startup of the *Fábrica do Futuro* the learning factory of the Escola Politécnica da Universidade de São Paulo. The *Fábrica do Futuro* is one of the first learning factories in Brazil and the first of its kind in a Brazilian university.

The learning factory aims to connect industry and university research by showcasing state-of-the-art technologies such as computer vision for quality control, additive manufacturing for complex components, autonomous transport for intralogistics, while combining them with traditional methods such as lean manufacturing and logistics.

The scope of this work is to startup the factory with its first assembly line of skateboards. Under the scope of this work is mainly the definition of an optimized factory layout and the definition of internal processes, while also procuring all the necessary means to startup the factory. The objective is to have the factory ready to implement industry 4.0 and logistics 4.0 ready technologies into the assembly lines.

Chapter 2 presents the necessary definitions for a common understanding of the topic, while also including a technology review of logistic 4.0 enabling technologies.

Chapter 3 presents the two main methods utilized to design and optimize the assembly process and define an optimized factory layout. For the first part traditional time and motion study is utilized, while for the second part Muther's systematic layout planning is described.

Chapter 4 shows the analysis and the results of the implementation of both methods within the *Fábrica do Futuro*, to show how assembly times are reduced and intralogistics is optimized by applying the aforementioned methods.

Chapter 5 summarizes the findings, while also focusing on the next technologies, which should be implemented into the *Fábrica do Futuro* to achieve a state-of-the-art status in terms of industry 4.0 and logistics 4.0 readiness.

2 Literature Review

2.1 Learning Factory

As the practical part of this work is performed in a learning factory, instead of a conventional industrial facility, it is necessary to define a learning factory.

The term "learning factory" is composed by "learning" and "factory", thus a straightforward definition is created through the combination of a production environment with elements of teaching and learning (Wagner et al. 2012).

A changing business and manufacturing environment with the need for customer-specific products solutions, increasing dynamic requirements of products and shorter product life cycles require new flexible processes, agile technologies, and reconfigurable flexible manufacturing systems to cope with this context (Wagner et al. 2012; Muller et al. 2008; ElMaraghy 2009). A learning factory provides the space for engineering students and industry practitioners to learn about the potential of these new technologies in experimental and research environments (Abele et al. 2011; ElMaraghy et al. 2012; Wiendahl et al. 2014).

According to Abele et al., learning factories appear in six different varieties (Abele et al. 2015):

1. Learning factories for industrial application: environments, which enable companies and students and industry participants to enhance their competencies in production.
2. Learning factories for academic application: educational platforms, which deliver activity-based courses to students.
3. Learning factories for remote learning: functions as a bi-directional knowledge communication channel, enabling remotely located engineers and students/researchers to work on projects together.
4. Learning factories for changeability: transformable production platform, containing modules, which can easily be reconfigured, changing the factories layout and functionalities.
5. Learning factory for consultancy application: a learning factories for industrial applications with the key difference, that the factory is owned or co-owned by a consulting firm.

6. Learning factory for demonstration: factories containing demonstrators of future production scenarios' fundamental technologies.

The learning factory "*Fábrica do Futuro*" from the University of São Paulo is categorized as a learning factory for demonstration. This factory has the purpose to create awareness of new and promising technologies in the context of Industry 4.0 to industry stakeholders.

2.2 Factory Design

Changing dynamics in markets push factories into increasing a need to fulfilling individual needs of customers to maintain competitiveness, the role of logistics as a competitive edge to increase the response time of a company is therefore paramount (Wiendahl 2014).

An adequate way of increasing a factories' logistic efficiency is an appropriate factory concept, which contains the production means (manufacturing, assembly, transport and storage equipment), company structure, spatial characteristics (site, buildings, layout, and outdoor facilities), flows (energy, information, capital, communication, material, media and personnel) and the humans (Arnold et al. 2008). A complete factory design takes all the five design dimensions into account as seen in Figure 1.

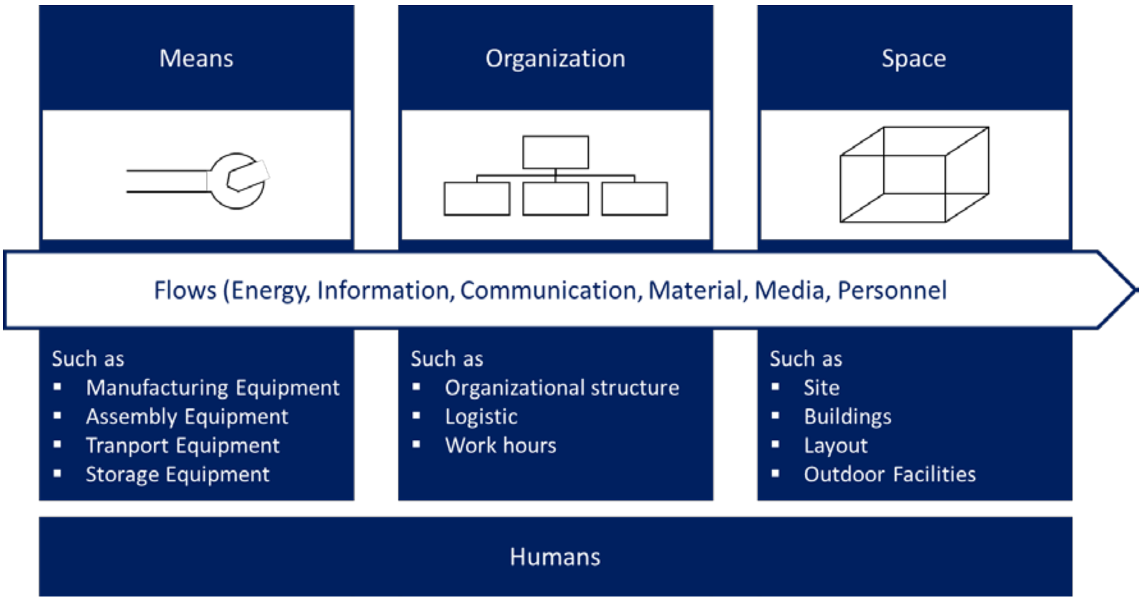


Figure 1 - Design fields of a factory (Arnold et al. 2008)

The structural design of a factory follows the four detailing levels illustrated in Figure 2. The first level takes the macro perspective of the factory site, going to the factory itself, the different areas contained in the factory layout and each workstation is contained in those areas.

The structural design assigns each design object into a detailing level and design dimension as per Figure 1. The correspondent detailing level of an object shows at which stage of the structure design an object is treated, although this does not necessarily mean, that an object cannot return on detailing levels below (Arnold et al. 2008). Which objects are more relevant for a factory design depends on the project itself while depending on the project, single objects can be left out entirely (Grundig 2014; Kettner et al. 1984).

	Means	Organization	Space
1. Site	▪ Technical Facilities Centrals	▪ Organizational Structure	▪ Land ▪ Building Fundament ▪ Outdoor Facilities
2. Factory	▪ Technical Facilities' Distribution ▪ Information Technology	▪ Production Concept ▪ Logistic Concept ▪ Structure	▪ Layout ▪ Structure ▪ Walls and Ceilings
3. Area, System	▪ Storage Means ▪ Transport Equipments	▪ Work Organization	▪ Build up
4. Work Station	▪ Procution Technology ▪ Manufacturing Equipments ▪ Other Equipments	▪ Quality Assurance Concept	▪ Workstation Design

Figure 2 - Detailing levels for structural development (Arnold et al. 2008)

The structural planning of a factory includes the assembly structure planning, which is a core of the work within the *Fábrica do Futuro*. Figure 3 shows the assembly structure planning and the necessary analyses to complete the planning process.

The *product structure analysis* explains the products' composition, its design, form, variants, and classification, including the products' parts (Ungeheuer 1986).

Manufacturing and assembly sequence analysis give an overview of all the activities, which are necessary to complete the product. It includes the sequence of activities and its needed resources, the capacities of equipment, stations and people and the efficiency of each activity (Pawellek 2014).

Material flow and transport analysis builds on the product structure and assembly sequence and its goal is to explain every movement of materials between all objects, such as workstations and storage units (Pawellek 2014).

Organization analysis aims at recognizing the need for a change a company's organizational structure after changes of the manufacturing and assembly processes (Pawellek 2007).

F*acilities analysis* separates into different facility classes according to (Pawellek 2014):

- Location and land analysis.
- Building analysis, taking the sustainable use and the overall flexibility into account.
- Installation analysis, which includes heating, air conditioning, and ventilation; sanitary technology, drainage, fire protection and electrical installations, for example.
- Station, equipment and tool analysis of machines, tools, storage units, transportation means, for example.

Personnel analysis aims at discovering if process changes have an impact on the demand for workers (Pawellek 2014).

Cost structure analysis is fundamental to display the economic impact of technical and organizational changes (Pawellek 2014).

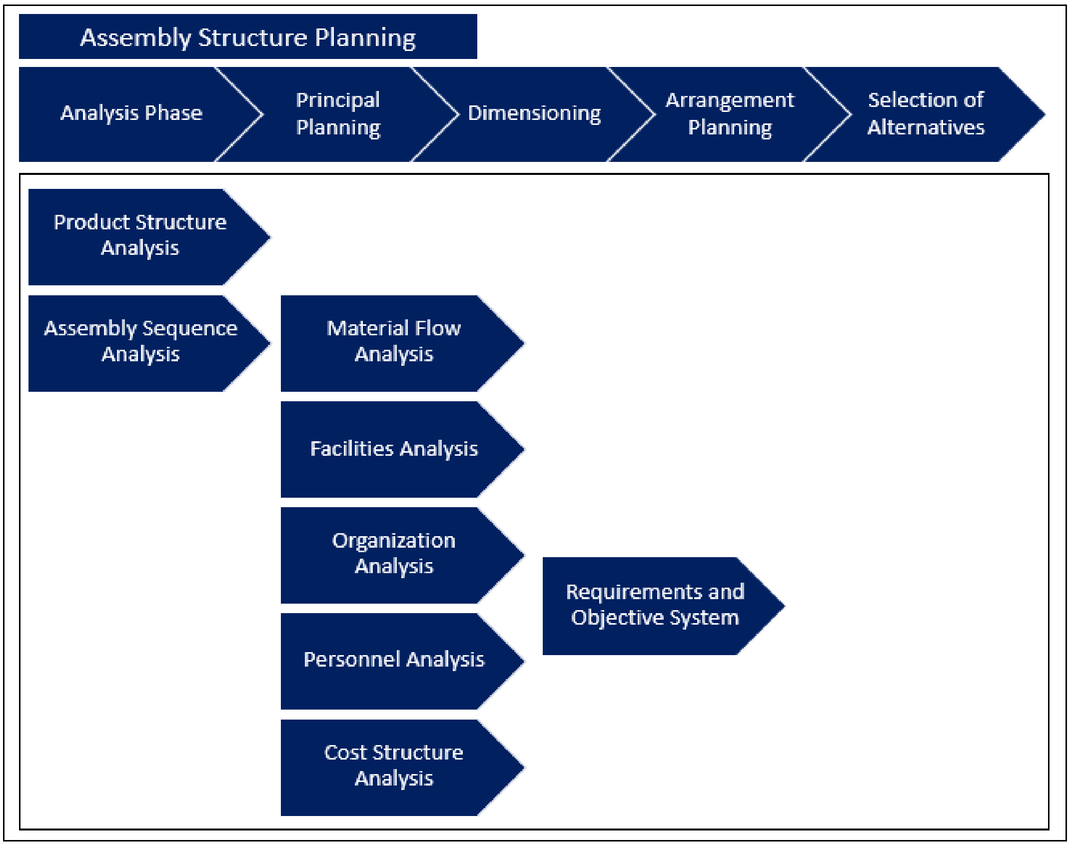


Figure 3 - Planning Process for Assembly Structures (Pawellek 2014)

The specific analyses, which were performed for the planning of the assembly process and subsequent layout and factory design are specified in Chapter 3.

2.3 Motion and Time Study

As per Barnes motion and time study is defined by the analysis of the methods, materials, tools, and equipment used to perform a piece of work (Barnes 1980). Motion and time studies follow four distinct purposes. Firstly, finding the most economical way of performing the specified procedure. Secondly, the standardization of the applied methods, material, tools and equipment. Thirdly, the accurate determination of the required time for a qualified worker to complete the tasks at a reasonable pace and lastly the necessary training of workers to utilize the defined methods.

Motion study by itself is the study, following the purpose of eliminating unnecessary motions and optimizing the work sequence, of all the required motions to perform a task (Barnes 1980). In this way finding the most economical way of operating is done through a systematic analysis of the applied methods, materials, tools and equipment.

A written standard practice is the result of the standardization of the results of the motion study. This standard practice contains all the necessary information to clearly define all aspects of the motions, material, machines, and pieces of equipment, including the conditions surrounding the worker (Barnes 1980).

The determination of the time standard is done through breaking down a task in activities and the amount of time required by every activity adjusted by a rating factor, which accounts for the pace in which the worker worked during the time study in comparison to the normal situation (Barnes 1980). This adjusted time is called basic or normal time (Barnes 1980; Slack et al. 2013). The result of adding time allowances due to personal time, fatigue and delay to the normal time is called standard time (Barnes 1980; Slack et al. 2013).

The training of the operator to perform the established standards is the culmination of every motion and time study as there is no value in the effort put on developing a new standard if the operator doesn't adopt it (Barnes 1980).

2.4 Lean Manufacturing and Poka Yoke

The concept of Poka Yoke appeared due to the limitation of sampling in a production process to detect errors. Poke Yoke aims on guaranteeing 100% inspection levels without increasing efforts prohibitively, like 100% end-of-line inspections.

Two basic concepts are followed to enable 100% inspection, which is an immediate feedback for action after production mistakes occur and avoiding the separation between operation and inspection, thus Poka Yoke can be defined as any mechanism to detect a mistake and correct it before it becomes a defect, which enables source inspection (Shingo 1986).

Guaranteeing source inspection prevents mistakes during execution, allows immediate mistake recognition through direct feedback during execution, immediate stop of execution to correct mistakes immediately and preventing defect parts to be passed on to the downstream production process.

Poke Yoke can be classified in two dimensions, according to the setting and the correcting function applied in each example. The setting function determines how the Poka Yoke tool detects an abnormality in the operation, while the correcting function determines how a Poka Yoke informs on a detected abnormality.

The setting function is enabled in three different ways, a *contact method*, a *fixed value* or a *process step*. The *contact method*, which identifies mistakes whether or not contact is established between the device and some feature of the product. The *fixed value* determines an abnormality, when a given number of movements is made. The *process step* determines whether the established steps or motions of a procedure are followed.

The correcting function is enabled through *control types* and *warning types*. The *control type* is defined by Poka Yokes, which force machine lines to shut down as long as the defect or abnormality is present, while *warning types* alert workers through buzzers and lamps, when the Poka Yoke is activated.

The figure below summarizes the different combinations of Poka Yoke functions:

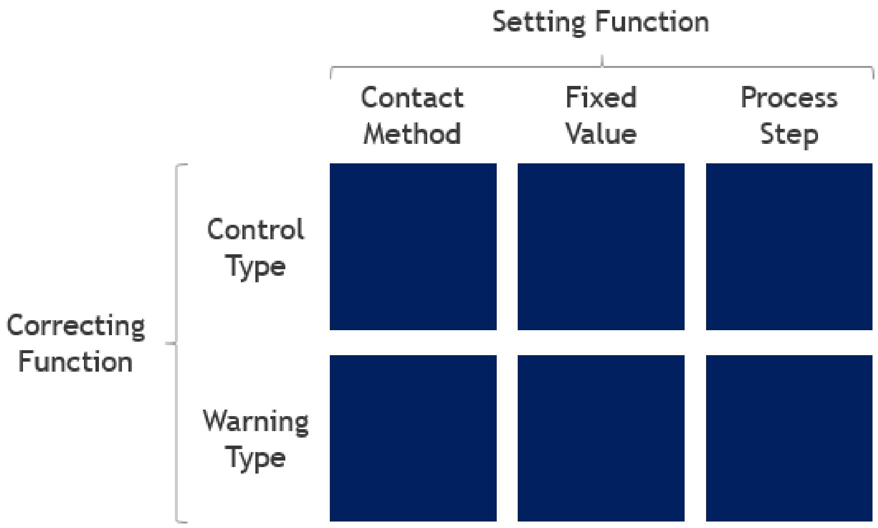


Figure 4 –Poka Yoke Classification (Shingo 1986)

2.5 Logistics 4.0 and technological enablers

To accurately define Logistics 4.0 it is necessary to define the meaning of Industry 4.0, as Logistics 4.0 is defined by (Oeser 2018) as the impact of Industry 4.0 into logistics (2018).

Industry 4.0 according to (Barreto et al. 2017)encompasses integrating and developing innovative information and communication technologies into industries by focusing on intelligent networking of products and processes throughout the value chain to achieve greater efficiency and novel offering for customers (2017). The main features presented by Industry 4.0 are clustered into four distinct categories (Tjahjono et al. 2017):

- Vertical networking of smart production systems
- Horizontal integration via a new generation of global value chain networks

- Through-life engineering support across the entire value chain
- Acceleration through exponential technologies

In this sense Logistics 4.0 contemplates the network of processes, objects, supply chain participants and customers through information and communication technologies into decentralized decision making structures to increase efficiency and effectiveness (Oeser 2018; Alicke et al. 2016). Furthermore, Industry 4.0 focuses on integrating the industrial production landscape, while Logistics 4.0 focuses on integrating processes through novel information and communication technologies (Oeser 2018).

The next sub-chapters are a high-level overview of the information and communication technologies involved in enabling and accelerating Logistics 4.0, the figure below lists technologies enabling Logistics 4.0.

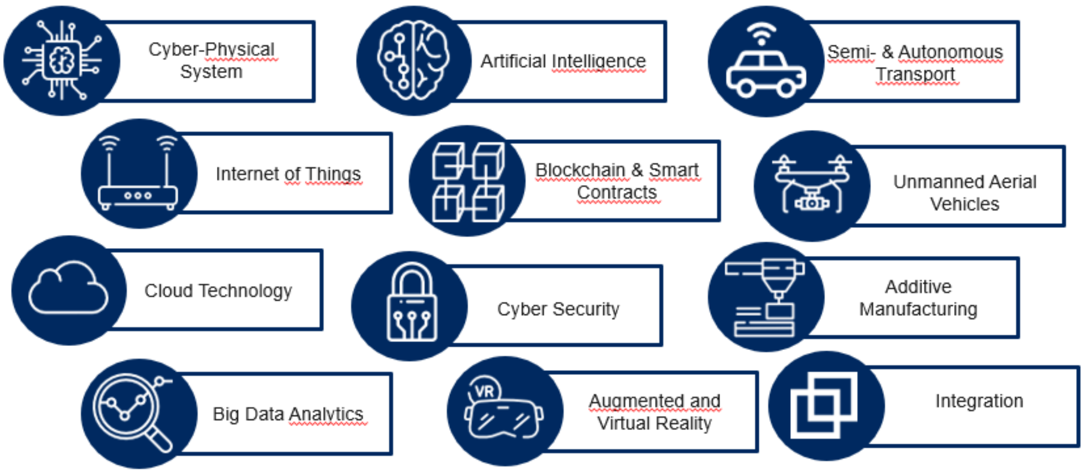


Figure 5 - Technological enablers for Logistics 4.0

2.5.1 Cyber-Physical Systems

Cyber-physical systems (CPS) are physical and engineered systems composed by sensors, actuators, control processing units and communication devices, which enable the monitoring, coordination and integration by computer and communication systems (Barreto et al. 2017; Rajkumar et al. 2013). The general architecture of a CPS is presented in the following figure.

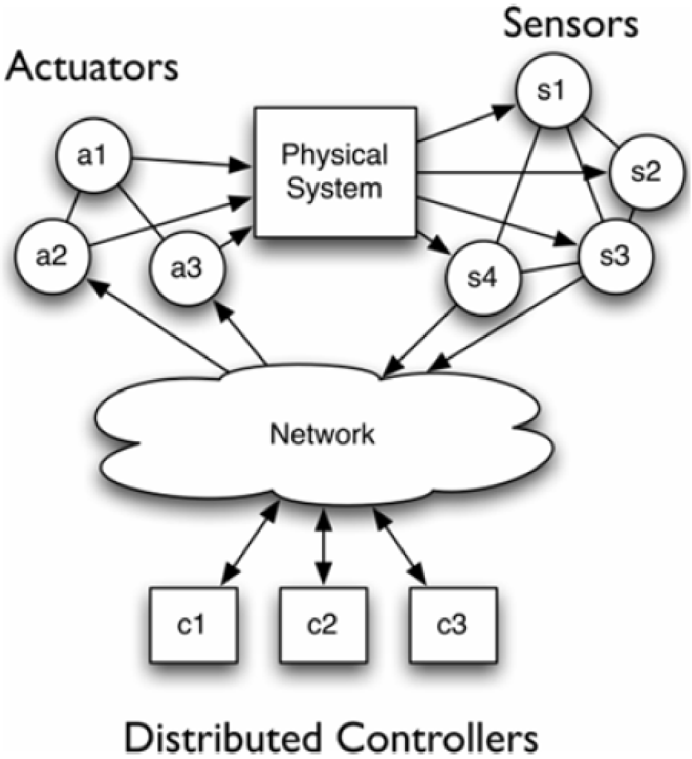


Figure 6 - General architecture of cyber-physical systems (Jeschke et al. 2017)

CPS lies in the center of several technologies as it plays a fundamental role in integrating digital technologies into hardware capable of coordinating processes as they, for example, make it possible for suppliers to gather real-time updates regarding consumption at the buyer's site, fundamentally changing disposition and production (Hofmann and Rüsch 2017).

2.5.2 Internet of Things

A simple definition of the Internet of Thing (IoT) is that it enables a "*world where basically all (physical) things can turn into so-called "smart things" by featuring small computers that are connected to the internet*" (Fleisch 2010).

In the context of Logistics 4.0 IoT enables connecting assets, systems and processes, which allows real time and networkwide visibility of end to end inventory flows (Gaus et al. 2018). This creates the possibility of establishing new ecosystems in which planning moves from forecasting to utilizing real-time information flows from node to node across the supply chain network (Daecher et al. 2018).

IoT distinguishes itself from the "ordinary" internet, because the nerve end of IoT are low-end and low energy consumption computers and not full-blown computers (Fleisch 2010).

2.5.3 Cloud Technology

Cloud technology and computing enables businesses to receive on-demand network access to shared computing resources, such as networks, servers, storage, applications and services (Holtkamp et al. 2010). Currently companies offer horizontal cloud solutions, which enable broad usage of cloud offering for any type of customer. The importance of vertical cloud offerings, such as cloud services designed specifically for supply chains is a phenomenon still in development which should enable according to Holtkamp et al the following aspects:

- Definitions of standard logistics business objects
- Tools for developing logistics specific IT applications
- Integration of local logistics systems
- Design of logistics processes
- Execution of logistics processes digitally

This will enable scaling of individualized logistics services for supply chain partners (Holtkamp et al. 2010).

2.5.4 Big Data and Analytics

According to (Hashem et al. 2015) Big Data "is a set of techniques and technologies that require new forms of integration to uncover large hidden values from large datasets that are diverse, complex, and of a massive scale" (2015). This definition contemplates the 4V's of Big Data, namely volume, variety, velocity and value, those are described by Hashem et al as follows:

- **Volume**: Data of all types generated from various sources. The main benefit of increasing volumes of data include the possibility to discovering patterns through data analysis (Laurila et al. 2012)
- **Variety**: Structured or unstructured data of distinct types collected from various sources.
- **Velocity**: Speed of data transfer.
- **Value** :Process of uncovering value from datasets of distinct types and rapid generation (Chen et al. 2014).

The benefit of these capabilities for logistics can be seen on increasing the resilience of supply chains through risk mitigation, which is enabled by analyzing large dataset available throughout the supply chain (Witkowski 2017).

2.5.5 Artificial Intelligence

The use of artificial intelligence and mainly machine learning and cognitive computing in logistics enables supply chains to be monitored and through uncovering patterns automate decision-making within digital supply chains (Gaus et al. 2018).

Furthermore, this enables businesses to bypass the bullwhip effect and also capitalize on influencing consumer demands through targeted prince incentives and other means (Renner et al. 2018). Computer vision, although enabled through artificial intelligence, is discussed in the chapters related to unmanned aerial vehicles and autonomous transport as this is one of the main technological enablers of this topic.

2.5.6 Blockchain and Smart Contracts

Blockchain is a decentralized and distributed ledger utilized by users in cooperation enabling secure data exchange within the network without the need of intermediaries (Jakob et al. 2018; Christidis and Devetsikiotis 2016).

Smart Contracts were coined by Szabo as "computerized transaction protocol that executes the terms of a contract" (1994). This enables the fulfillment of contractual conditions through payment terms, liens, confidentiality and enforcement to minimize the need of trusted intermediaries (Jakob et al. 2018).

For supply chains the combination of blockchain, smart contracts and IoT enables orders to be automatically placed on vendors according to contractually established criteria, while financial flows are enforced through smart contracts automatically and contract fulfillment is analyzed through IoT enabled hardware (Gaus et al. 2018).

2.5.7 Cyber Security

The importance of cyber-security goes hand in hand with the utilization of cloud-based systems, IoT, Big Data and other technologies, as the increasing reliance on technology also increases the need to protect data and information for a business to be successful (Barreto et al. 2017).

New technological most of the time reveal unpredicted security risks, thus an effective and efficient cyber-security initiative ensures the ability of businesses to protect information assets and IT infrastructure (Bosworth and Kabay 2002).

2.5.8 Augmented and Virtual Reality

Simple definitions of Augmented Reality (AR) and Virtual Reality (VR) go back to 1997, where Azuma described VR as immersing an user in a completely synthetic environment, while AR is the overlay of virtual information into the real environment to enrich human senses and abilities (Azuma 1997; Cirulis and Ginters 2013).

In the sense of logistics 4.0, AR is commonly represented for innovative solutions to enhance worker performance for order picking or for assisting planning of logistic systems (Schwerdtfeger and Klinker 2008; Reif and Walch 2008). VR solutions for logistics focus on training environments, such as instructing order picking processes to workers in a virtual environment (Reif and Walch 2008).

2.5.9 Semi and Autonomous Transport

Semi- and autonomous transport in logistics 4.0 finds many applications inside and outside facilities. Completely autonomous solutions range from autonomous trucks for product distribution and Automated Guided Vehicles (AGV) transporting goods inside the shop floor (Lourenço et al. 2016; Zhang et al. 2018). Semi-autonomous transport finds common application on the concept of platooning, in which electronically coupled truck convoys with small gaps in between to improve aerodynamics and reduced personnel costs (Tsugawa et al. 2016).

2.5.10 Unmanned Aerial Vehicles

Unmanned aerial vehicles (UAVs) find several applications in logistics such as applying pesticides in precision farming or delivering small packages through the air (Wrycza 2019; Wolfert et al. 2017).

The use of UAVs in urban areas are subject to dynamic environment changes, which require additional safety layers, such as systems to monitor the entire delivery process (San et al. 2018). Even though research into UAVs for last-mile deliveries is vast, the real applications in logistics remain scarce and so far UAVs find more mature applications in Industry 4.0 related areas, such as inspection and maintenance of difficult to reach facilities (Chan et al. 2015).

2.5.11 Additive Manufacturing

Additive manufacturing is a production process in which a product is built up in printed layers, the whole production process is controlled by computers (Knofius et al. 2016).

The impact of additive manufacturing in logistics and mainly on the supply chain are vast, such as reducing distribution costs by offering lighter products with more complex geometries or by eliminating most of distribution costs through decentralized manufacturing, in which consumers can create their own products or spare parts (Knofius et al. 2016; Attaran 2017).

2.5.12 Integration

In Logistics 4.0 integration refers to "the process of linking together different computing systems and software applications physically or functionally, to act as a coordinated whole logistics flows" (Kayikci 2018). This can be achieved in three distinct ways according to Wang et al. (2016):

- Horizontal integration through value networks
- Vertical integration and networked logistics systems
- End-to-end digital integration of the entire value chain

Software as a Service applications and application programming intefaces (API) allow the communication between back-end of systems and the creation of digital ecosystems for supply chain participants (Kayikci 2018).

3 Methods

Several methods are applied in sequence to enable the factory design of the Fábrica do Futuro. This chapter provides the theoretical background to perform the required analyses for the assembly process planning and the subsequent layout planning and *Mizusumashi* design.

The motion and time studies are required to analyze the assembly process firstly. The outcome of this analysis is sufficient information to firstly, implement necessary adjustments in the assembly process with the goal to reduce cycle times, secondly distribute the assembly activities into different workstations to perform line balancing and finally establish the material flows between each workstation. Barnes defined the presented methodologies (1980).

The material flow analysis provides the data to perform the systematic layout planning according to Muther (1973). The outcome of the systematic layout planning is an optimized plant layout of the factory based on material flow and non-flow restrictions.

After the layout definition, the *Mizusumashi* design is presented, which is the intralogistics solution of choice for workstation replenishment.

3.1 Motion and Time Studies for Assembly Processes

Motion and time studies aim at generating better production methods. For that unnecessary work is eliminated, operation elements should be combined, sequences are changed, and critical operations have to be simplified, if possible (Barnes 1980).

To do so the first step is performing a process analysis. A process analysis sums all activities needed to perform the process by clearly defining transportations distances, describing and explaining each step. The result of the process analysis is a process chart, as exemplified below in Figure 4.

Activities can be symbolized by the American Society of Mechanical Engineers (A.S.M.E) Standard in five different chart symbols depictured in Figure 5.

Operations represent the main steps of a process, while all others are considered auxiliary operations, it usually involves a modification of a part, material or product (Barnes 1980).

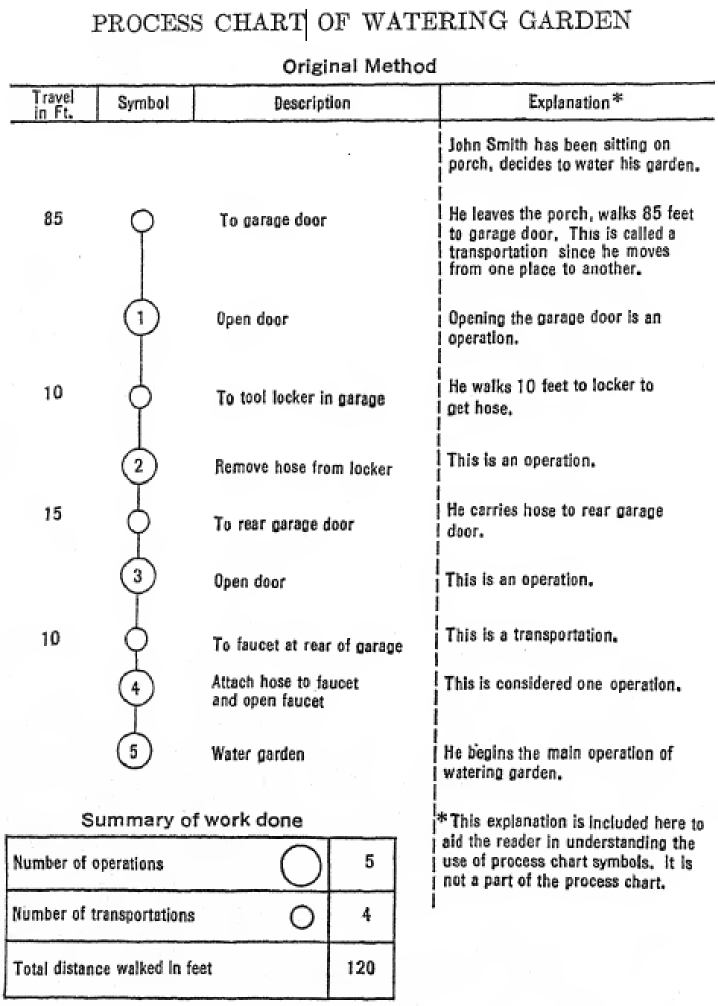


Figure 7 - Example of a Process Chart

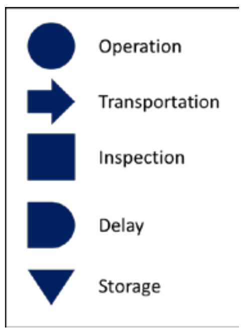


Figure 8 - The A.S.M.E. standard process chart symbols (American Society of Mechanical Engineers 1947)

The *Transportation* symbol stands for every auxiliary operation in which a part or an object is moved from one place to another (Barnes 1980).

The *Storage* and *Delay* symbol both indicate that the part or object is stored for a determined period. While the differentiation between storage and delay is not necessary, one can use the delay symbol to signalize, that the object is stored temporarily at a place in contrast to a permanent and controlled storage (Barnes 1980).

The *Inspection* symbol represents an inspection in term of either quality or quantity. Quantity inspections can be done through measuring, counting or weighing, while quality inspection usually requires the testing within a predetermined standard (Barnes 1980).

The symbols can appear in combination, as an example, a circle within a square depicts an operation combined with an inspection, this is, for example, the case in Poka Yoke devices, which parallel to the operation perform the inspection autonomously (Slack et al. 2013).

Subsequently, the operation is analyzed for improvement opportunities. *Appendix A* provides a checklist of questions to guide the process optimization (Barnes 1980).

Another fundamental aspect of time study is the determination of standard process times. While several methodologies to do so were presented in various works of literature, video recording is a simple and efficient way of establishing process times through samples. Every operation step of each sample is then measured for the *measured time*.

The goal is to establish a *standard time*, which is the measured time adjusted by a work rate rating factor and personal, fatigue and delay allowances.

The *rating factor* accounts for the different work speeds of operators utilizing the company standard as a benchmark (Barnes 1980). The rating value is a percentage, in which every value above 100% signifies a work rate superior to the company standard, while a value below means the operator performed the activity at a lower speed compared to the company standard. Rating factors can be applied to single activities or applied to all activities in a process sample at once in a simplified way. Adjusting the measured time with the rating factor creates the *normal time* as seen in the equation below:

$$Normal\ Time = Measured\ Time \times \frac{Rating\ in\ Per\ Cent}{100}$$

Personal allowance accounts for the percentage a worker requires to fulfill her or his personal needs, ranging between 2 and 5 percent in an 8-hour shift of light work (Barnes 1980). *Fatigue allowance* is proportional to the physical demand of the performed activity work. *Delay allowances* consider avoidable and unavoidable delays caused by the operator, machine or an outside force (Barnes 1980). The single allowances are summed into an allowance factor, which is used to calculate the standard time of the activity, Table 1 shows various allowance factors based on different work conditions.

Allowance factors	Example	Allowance (%)
Energy needed		
Negligible	none	0
Very light	0–3 kg	3
Light	3–10 kg	5
Medium	10–20 kg	10
Heavy	20–30 kg	15
Very heavy	Above 30 kg	15 to 30
Posture required		
Normal	Sitting	0
Erect	Standing	2
Continuously erect	Standing for long periods	3
Lying	On side, face or back	4
Difficult	Crouching, etc.	4 to 10
Visual fatigue		
Nearly continuous attention		2
Continuous attention with a varying focus		3
Continuous attention with a fixed focus		5
Temperature		
Very low	Below 0°C	over 10
Low	0–12°C	0 to 10
Normal	12–23°C	0
High	23–30°C	0 to 10
Very high	Above 30°C	over 10
Atmospheric conditions		
Good	Well ventilated	0
Fair	Stuffy/smelly	2
Poor	Dusty/needs filter	2 to 7
Bad	Needs respirator	7 to 12

Table 1 - Allowance factors for different work conditions (Slack et al. 2013)

The *standard time* is the normal time adjusted by the allowance factor and is calculated as follows:

$$Standard\ Time = Normal\ Time\ \times \frac{100}{100 - Allowance\ in\ Per\ Cent}$$

The creation of the process chart after an initial process analysis, the subsequent operations optimization achieved by the operations analysis and the calculation of standard times based on video recorded samples concludes the motion and time study. Based on the generated data it is possible to continue the factory design with the systematic layout planning.

3.2 Systematic Layout Planning

Layout planning has the primary objective of facilitating the manufacturing process, while additional objective may include minimizing material handling, through reduction of traveled distances and times; maintaining the flexibility of the factory, in case of changes; enabling high turnover of work-in-process; reducing investments in equipment, utilizing floor space effectively; increasing labor efficiency and proving a safe and comfortable work environment (Muther 1973).

Systematic Layout Planning (SLP) is a method divided into four phases, which is used in detailing a factory layout starting from material flow analyzes and an initial layout. The method described by Muther goes through following phases:

- *Phase I – Location* is the determination of location, which is to be laid out, it does not have to be a new site but can also include necessary modifications depending on other constraints or relaxations.
- *Phase II – General Overall Layout*, which establishes the general arrangement of the area. This phase aims at bringing together the basic flow patterns of the factory regarding general size, relationships, and configuration of every significant area.
- *Phase III – Detailed Layout Plan*, which determines the actual place of every piece of machinery and equipment. This phase also takes utilities and services as well.
- *Phase IV – Installation*, which includes the planning of the change implementation and the implementation itself.

3.2.1 Flow Relationships

Phase I is not relevant for the scope of this work, as the location is already selected and empty and, thus no location or space change is triggering the utilization of the method.

Phase II, on the other hand, is relevant, which starts with a volume-variety analysis of the factory. The output of this analysis is a Product-Quantity Chart (P-Q Chart) as exemplified in Figure 6.

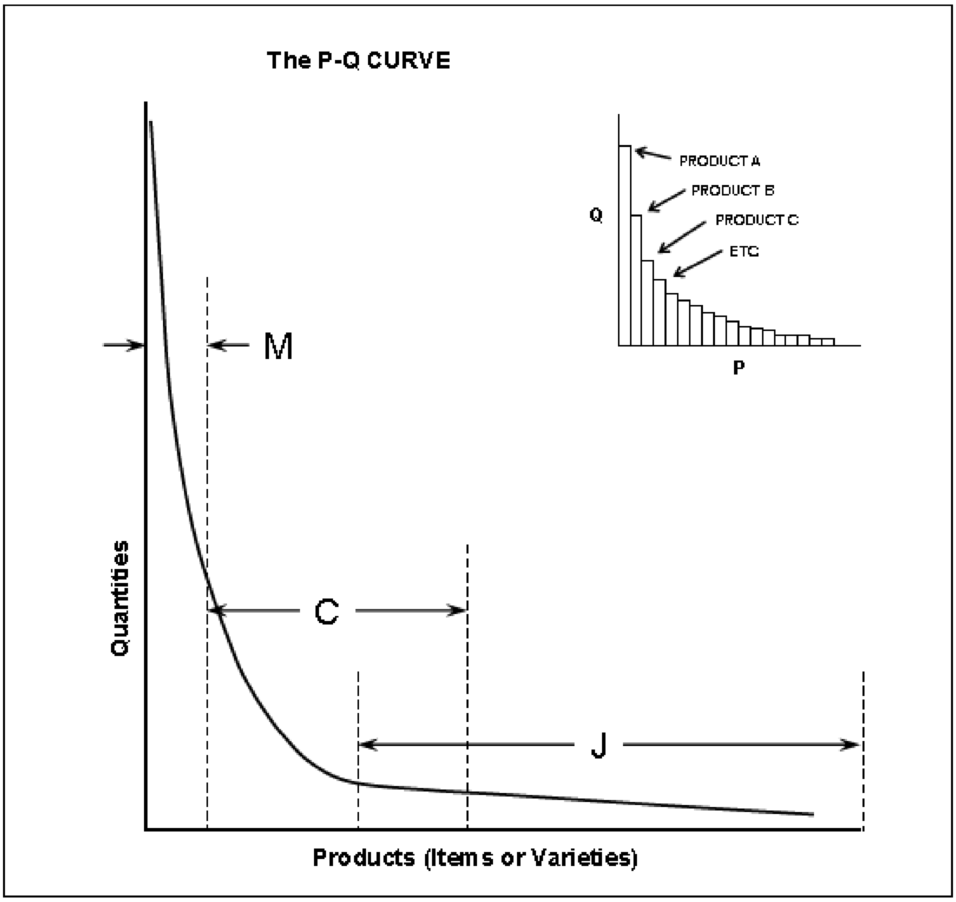


Figure 9 - Example of P-Q Chart (Muther 1973)

The P-Q Chart delivers valuable information by comparing all the offered products and its varieties against the actual production quantities of each product in a determined period. In a general way, this chart serves as guidance to choose the appropriate layout type. In the example above the products contained in de region *M* are suited for mass production, those in region *J* are potential candidates for jobbing processes and the region *C* is a gray zone between both types, in which products are usually fabricated in lots or any of the preceding alternatives on a case-by-case basis (Groover 2007).

The chart also recommends the most suitable analysis method to analyze the material flow as seen in Figure 7. Muther provides three different methods for determining material flows within a factory: the operation process chart, the multi-product process chart and the from-to chart.

For the few product varieties with very high production quantities it is recommended to create a detailed operation process chart. An operation process chart is similar to the process chart presented in chapter 3.1, the difference being the inclusion of moved weights between every operation and storage units.

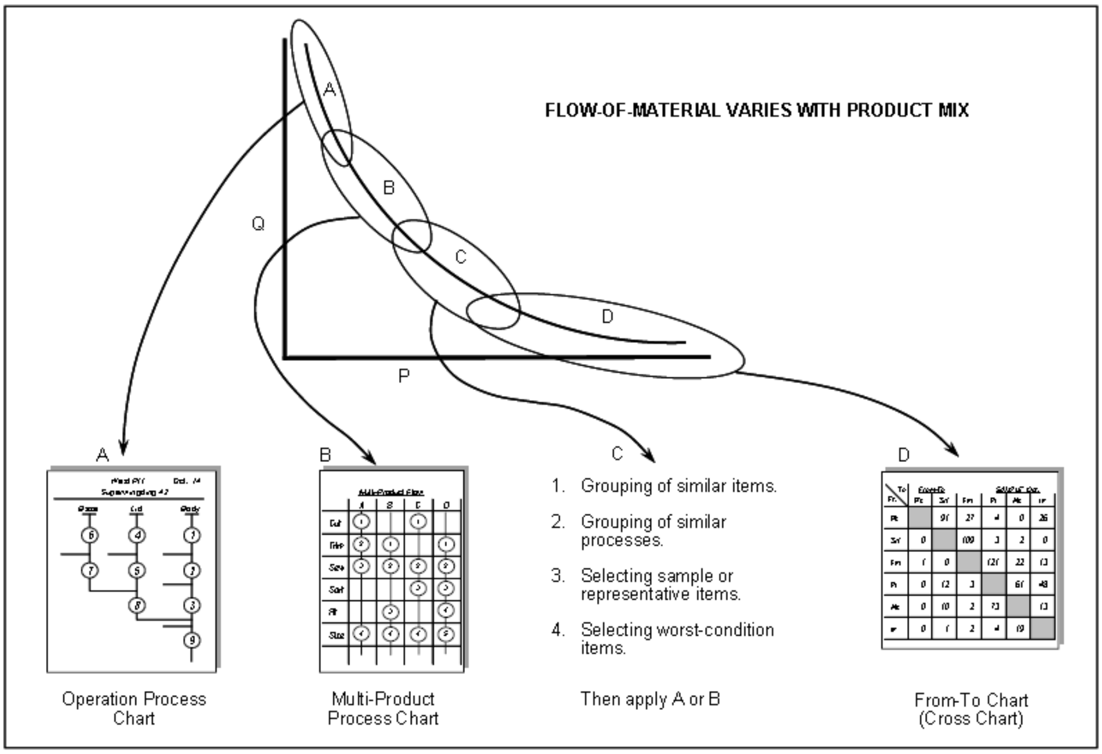


Figure 10 - Material flow analysis method recommendation based on the P-Q Chart (Muther 1973)

A multi-product process chart aligns several products' processes side by side enabling the recognition back-tracking. The objective is to optimize the products in conjunction by minimizing back-tracking through the reallocation of workstations and machinery. This chart is recommended for six to ten product variant at once, while the operation process chart is recommended for up to 4 variants (Muther 1973).

The from-to chart is the method of choice when the amount of product varieties is high, and the produced amount is relatively low. The from-to chart is a very flexible tool which can contain in a single chart all the information regarding moved weights between stations, machines, work centers, departments and docks (Muther 1973). An example of a from-to chart is presented in the picture below.

FROM \ TO	Shear 1	Notch 2	Draw 3	Pierce 4	Bend 5	Trim 6
Shear 1	–	ABC 3	–	EF 2	–	–
Notch 2	–	–	BD 2	AC 2	–	–
Draw 3	–	–	–	–	BCDF 4	C 1
Pierce 4	–	–	CEF 3	–	A 1	–
Bend 5	–	–	–	–	–	BDE 3
Trim 6	–	–	–	–	–	–

Figure 11 - Example of a From-To Chart (Muther 1973)

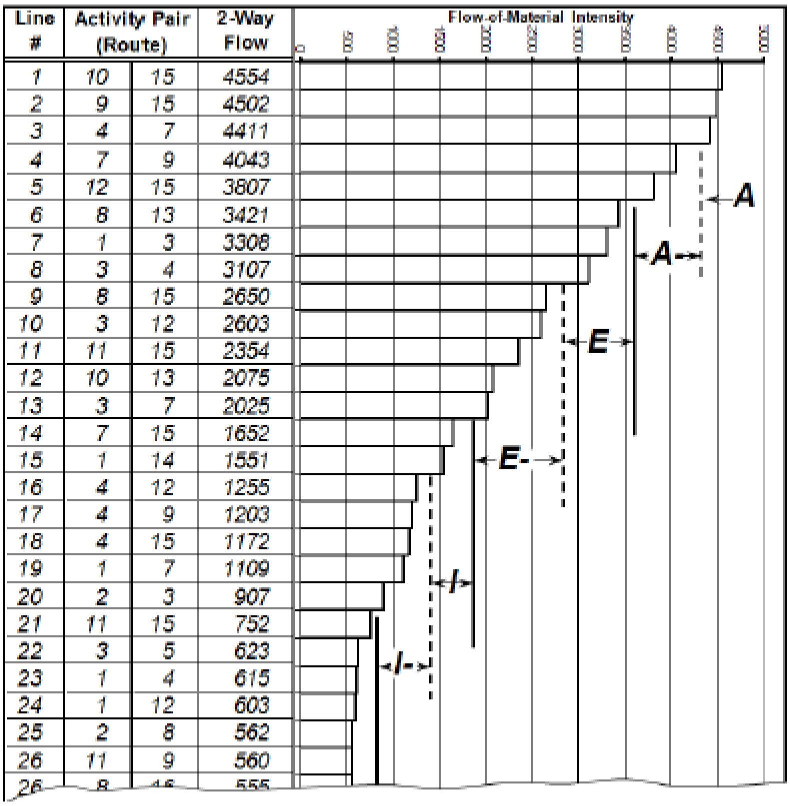
After the analysis of every product variety in its respective charts, all the results are summarized in a single from-to chart (Muther 1973).

The next step is to rank the routes by converting the intensity of the material flow into a vowel-letter scale. To do so, the routes are ranked in decreasing order of transported weight or the flow intensity calculated by multiplying the transported weight with the traveled distance. The division of the rank of the route by the combination of possible routes gives a percentage value, which can be categorized into the vowel-letter rating scale as shown in Table 2.

Classification	Range	
A	2%	5%
E	3%	10%
I	5%	15%
O	10%	25%
U	25%	100%

Table 2 - Vowel-Letter rating scale for routes (Muther 1973)

An example of the classification of routes is in Figure 9. This example uses a further segmentation of the vowels by adding a minus sign after each letter and, thus doubling the number of classes.



Line #	Activity Pair (Route)		2-Way Flow
1	10	15	4554
2	9	15	4502
3	4	7	4411
4	7	9	4043
5	12	15	3807
6	8	13	3421
7	1	3	3308
8	3	4	3107
9	8	15	2650
10	3	12	2603
11	11	15	2354
12	10	13	2075
13	3	7	2025
14	7	15	1652
15	1	14	1551
16	4	12	1255
17	4	9	1203
18	4	15	1172
19	1	7	1109
20	2	3	907
21	11	15	752
22	3	5	623
23	1	4	615
24	1	12	603
25	2	8	562
26	11	9	560
26	8	15	555

Figure 12 - Classification of Routes through the Vowel-Letter Convention (Muther 1973)

3.2.2 Other than Flow Relationships

Material flow by itself is not enough to establish an optimized layout, thus several other non-flow related relationships within the factory are accounted for, according to Muther (1973):

- Supporting services should seamless integrate into main operations, thus some of the supporting areas need close proximity to determined areas.
- Plants which produce products with very low weights often don't need to focus on the flow relationships. In these cases, non-flow relationships are paramount for layout design.
- Service areas are also an issue as they might require proximity to enable shortened communication flows or for paperwork.

- Dangerous or dirty operations, for example, might compromise nearby operations even though flow data requires proximity between each operation. These cases require the definition of non-flow relationships which avoid proximity of operations in these cases.

The flow relationship chart follows the same classification as flow relationships, while adding two new classes to them (Table 3). The letters *X* and *XX*, signalize the need of an area to be distant of another for optimal results. While the letter *X* determines a set distance in the diagramming procedure of the following chapter the *XX* rating only requires an area to be as distant as possible.

Vowel	Lines	Closeness Rating
A		Absolutely Necessary
E		Especially Important
I		Important
O		Ordinary
U		Unimportant
X		Not Desirable
XX		Extremely Undesirable

Table 3 - Vowel-Letter Classification for non-flow Relationships (Muther 1973)

Figure 10 shows the non-flow relationships of each area in comparison to others, thus naming a specific class of relationship to each route. For documentation purposes it is important to the name the reason for a classification.

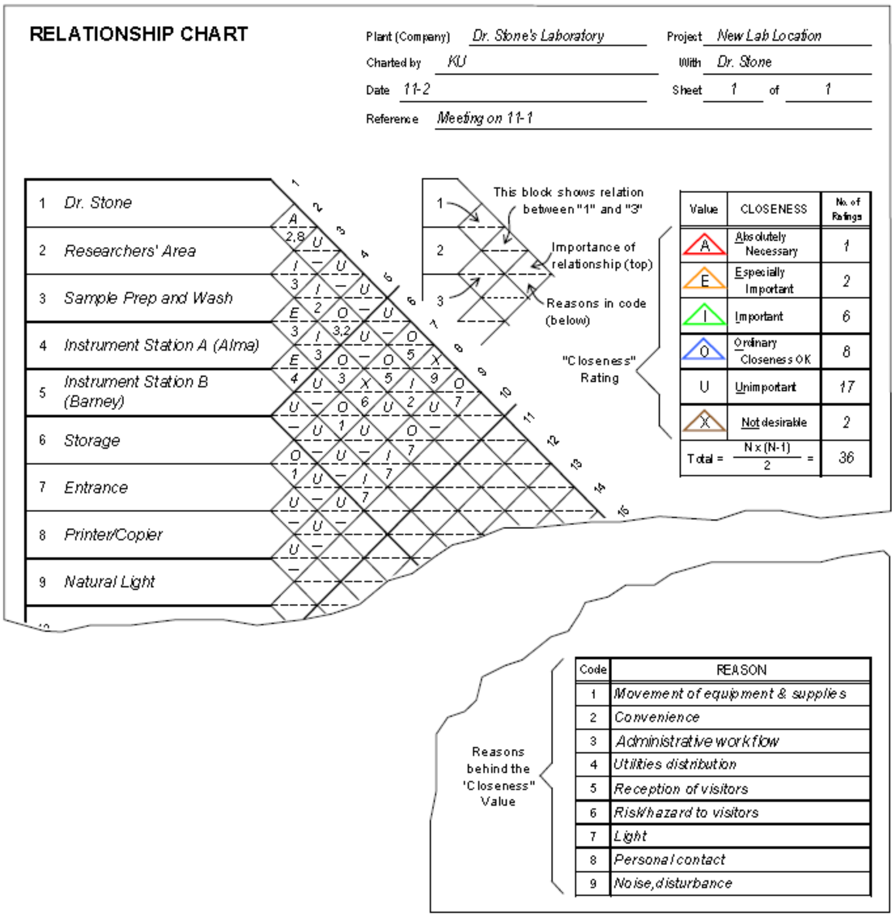


Figure 13 - Example of a Relationship Chart (Muther 1973)

3.2.3 Flow and/or Activity Relationship Diagram

The definition of the flow and non-flow relationships enable the creation of a diagram, which represents the new layout in a qualitative way. This diagram is created by mapping all relationships and their route importance, as per Figure 9. The graph is created by starting with the most important relationships, subsequently adding the latter. Figure 10 presents an example of the diagramming step-by-step (Muther 1973). The result of this phase is a qualitative schematization of the locations of specified areas.

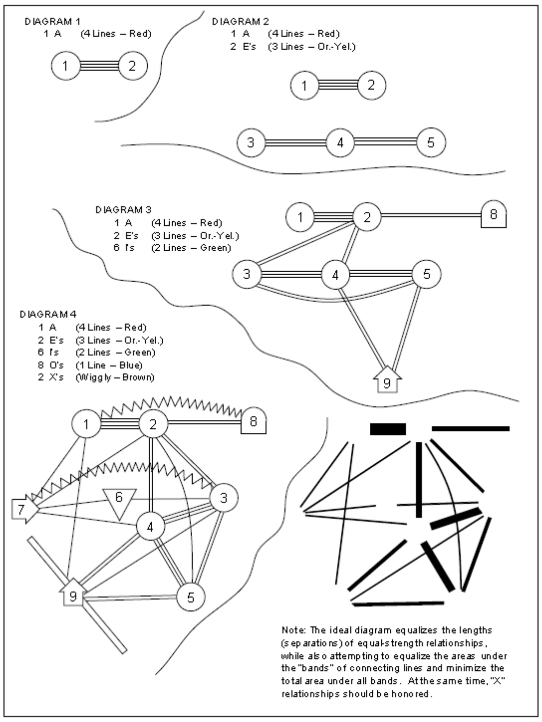


Figure 14 - Example of Flow and Activity Relationship Diagram (Muther 1973)

The elaboration of the flow and activity relationship diagram end phase II of the SLP method.

3.2.4 Space Determination

The next step is to transform the flow and activity relationship diagram into a space relationship diagram. The space relationship diagram is also known as block-layout. The block-layout maintains the flow intensity relationship , while also adding to the A.S.M.E symbols the area name and dimensions, thus enabling to scale the diagram (Muther 1973).

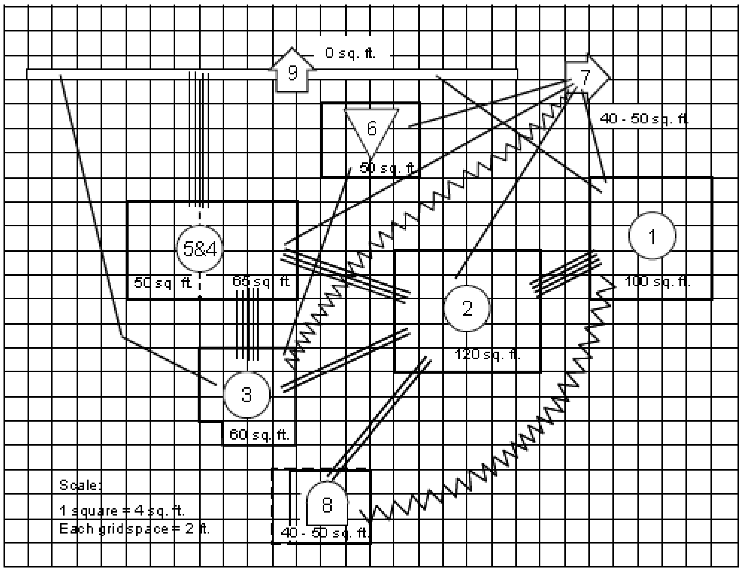


Figure 15 - Example of Block-Layout (Muther 1973)

The block-layout ends *Phase III* of the sequence presented in chapter 3.2.

3.2.5 Implementation

Phase IV goes further into the detailing of the layout by focusing on the workplace. It includes the definition of the standard work procedures in every workstation by including realized operation within the area, its times and a detailed layout of the workspace (Muther 1973).

This phase follows the same principles explained in chapter 3.1, by creating the process charts, performing the motion and time study, including an operations analysis, followed by the optimization of the workplace. Figure 13 shows the outcomes of this work.

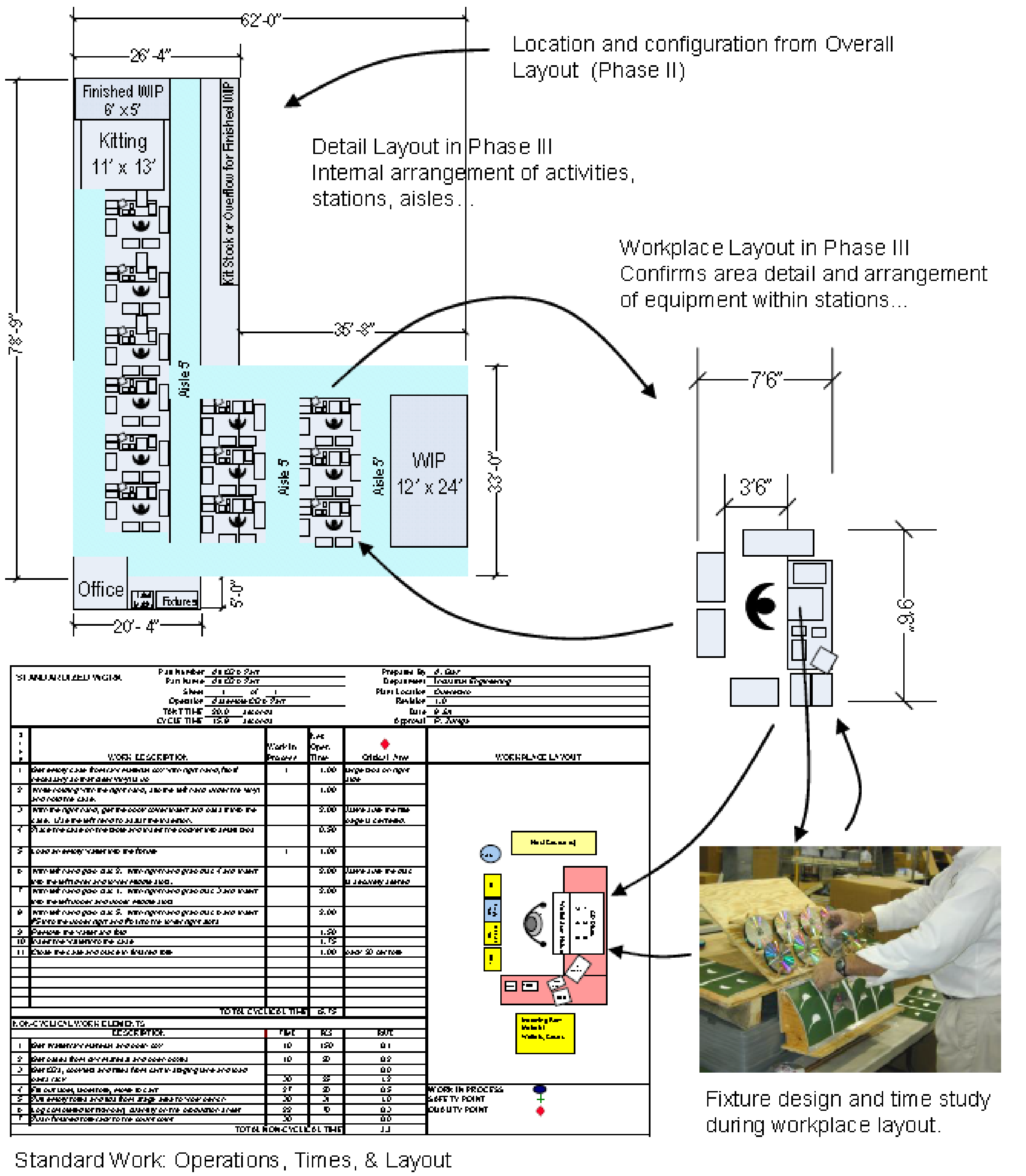


Figure 16 - Conclusion of Phase IV (Muther 1973)

4 Analysis of the Factory of the Future

The *Fábrica do Futuro* is a learning factory in its early stages. Thus all production related topics were still unplanned. The objective of this work is to plan the factory regarding production processes, plant layout, and internal logistics processes while utilizing the methods presented in chapter 3.

The production process within the *Fábrica do Futuro* is the assembly of a connected skateboard. It is a skateboard, which has a box, containing several sensors, attached to it.

In the context of this work the assembly process was elaborated and optimized, through a motion and time study to optimize the assembly process and the balancing of activities between the available workstations. The result of this step is a standardized and optimized process for the assembly of the skateboards within the factory.

The second step included the estimation of the material flows within the factory, the analysis of the available production space and its restrictions to perform the systematic layout planning of the factory. The result was an optimized layout.

The internal logistics processes are defined according to the estimation of the material flow within the factory. After the optimization of the assembly processes, the members of the project jointly defined a Mizusumashi as the intralogistics solution of choice for material replenishment at the workstations.

After the implementation and standardization of the new assembly and logistics processes within the new layout, it is possible to order the necessary tools, equipment and facilities to perform further tests needed to implement the final version of the factory design presented in Chapter 5.

4.1 Initial Time Study for the Skateboard Assembly

The objective of the time study is to calculate the estimated takt time of the process and the distribution of the workload in different workstations. Since this work started without an available assembly process this process had to be defined.

The time study can thus be divided into the preparation of the time study and the time study of the optimized process.

The preparation of the time study involved the initial definition of the assembly process and an analysis of each of the process steps, including the calculation of standard times, through several video analyses. This is followed by the optimization of the process to prevent common assembly mistakes through process variation and utilization of specialized tools and facilities. The optimization involved the use of prototypes to test the viability of the designed processes and of the tools itself.

After establishing the optimized process further video analyses of the newly designed process are made to calculate the standard times and takt times of the assembly process.

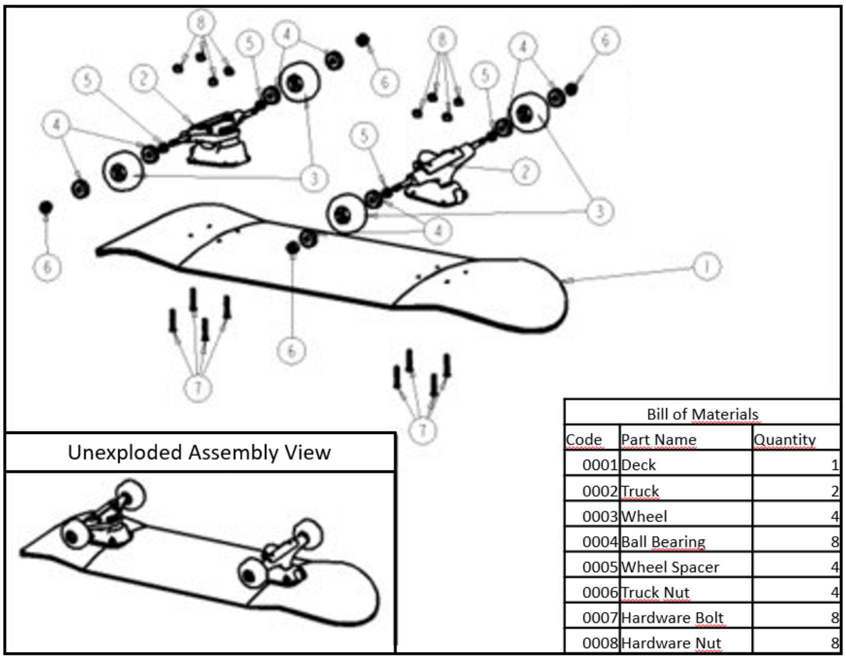
4.1.1 Preparation for the Study

An initial process assembly sheet derives directly from the bill of materials (BOM) and initial constraints to the assembly process. The BOM and the illustration of each of the components of the skateboard is presented in Figure 15. It is possible to note, that the connectivity box is not presented in the BOM nor in the skateboards of the same image, this is due to the connectivity box not being designed at the time of writing.

Since the purpose of the *Fábrica do Futuro* is mainly to present demonstrators of technologies to industry partners and interested people, the team initially defined that the assembly process should be performed in four different workstations.

Following the creation of the BOM each step of the skateboard assembly was analyzed separately without the assistance of specialized tools and equipment. The aim of this first analysis is to gather initial information on probable assembly mistakes and which operations present biggest improvement opportunities.

Initially it was defined, that several utilized materials should be scanned with a QR-Code scanner. Besides assembling the skateboard itself, the process should encompass the customization of the truck by applying different torque options and the application of the connectivity box, both of these processes were not analyzed in the preliminary analysis of the process, as the scope was not defined at the time of analysis.



Bill of Materials		
Code	Part Name	Quantity
0001	Deck	1
0002	Truck	2
0003	Wheel	4
0004	Ball Bearing	8
0005	Wheel Spacer	4
0006	Truck Nut	4
0007	Hardware Bolt	8
0008	Hardware Nut	8

Figure 17 - Bill of Materials of assembled skateboard excluding connected box

First tests were made to estimate the assembly time of a complete skateboard with all parts shown in Figure 15. A straightforward assembly process was established in which only an electric screwdriver and a wrench were utilized for assembly, while a workbench, a computer and a QR code scanner were also utilized in the process. Table 4 depict each step of the process to assemble the skateboard.

Throughout 10 assembly trials the assembly time varied from 5 minutes to 8 minutes, while the average assembly time lies on 6,5 minutes. Great time variances are explained due to assembly mistakes, mostly because lack of specialized tools:

- Activity 05 - concentrated most of the assembly mistakes, as securing the bolts from falling while mounting the truck through 4 bolts simultaneously.
- Activity 05 - securing hardware nuts while screwing the hardware bolts to fixate the trucks is difficult due to the lack of visibility of both sides of the skateboard at once, the consequence were several trials to both secure the nuts and screw the bolts correctly.
- Activities which require the skateboard to be held vertically - slowed down assembly times as they constrained movements by workers.

Number	Activity
01	Identify on computer screen which shape to pick. Pick shape the shape and place it with the bottom side facing upwars on workbench.
02	Grab the QR Code scanner, scan the shape's QR Code and return the QR code to its original position.
03	Turn shape 90 degrees and hold it onto the bench.
04	Pick and place 8 hardware bolts into the shape's truck holes.
05	Grab a truck and place it through 4 of the bolts, while securing the bolts from falling. Pick 4 hardware nuts and screw them onto the tip of the bolts. Repeat activity for other truck.
06	Grab the electric screwdriver and screw every bolt, while securing the hardware nut with a wrench. Return the electric screwdriver into original position.
07	Identify on computer screen which wheels to assemble. Scan each wheel with the QR Code scanner. Pick 8 wheel spacers, 16 ball bearings and place on each truck side, in order, a wheelspacer, a ball bearing, a wheel and another ball bearing.
08	Pick 8 truck nuts a screw on the tip o each truck side.
09	Grab the electric screwdriver and screw every truck nut. Return the electric screwdriver into original position.

Table 4 - Initial assembly process sheet

A new assembly process with simple prototypes for tools was established to minimize the assembly time variance and the reduction of the average assembly time.

To mitigate the assembly mistakes a few changes were made into the process. Figure 19 shows how the operation was done before the implementation of custom support to stabilize the board during assembly. Originally it was necessary to balance the board vertically, while assembling the bolts. The custom support allows the worker to separate the operation into placing the board onto the custom support and afterwards insert the bolts individually without the need to balance the board.

Figure 18 - Improvement of Operation O3

Operation O4 also presented some difficulties without additional support structures. To screw the nut onto the truck it is necessary to turn the board upside down, while the bolts are not fixated. This caused several assembly delays as turning the skateboard with no fixation for bolts makes them easily fall off of the truck holes. This was fixed by utilizing a custom cover, which covers the bolts and prevent them from falling off, while turning the skateboard around. A prototype can be seen in Figure 20.

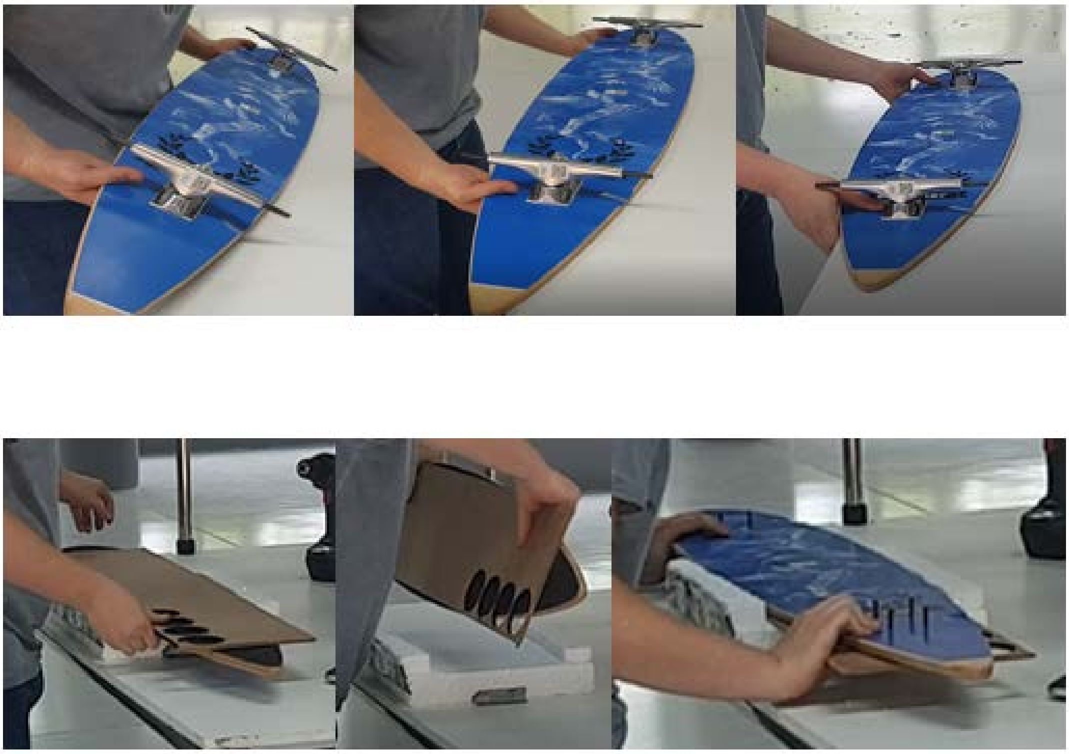


Figure 19 - Improvement of Operation O4

After making the changes into the assembly process, the complete assembly process is divided into 14 operations shown in Table 5. The allocation of different activities into work-stations was made by analyzing assembly times of each operation.

Activity Code	Activity Description	Activity Start Location	Activity End Location
O01	Look for needed deck, retrieve and place it on work station, bottom side up.	Work Station 1	Work Station 1
O02	Retrieve scanner, scan QR code from deck and place scanner on position.	Work Station 1	Work Station 1
O03	Turn deck around.	Work Station 1	Work Station 1
O04	Place 8 hardware bolts onto deck at respective holes.	Work Station 1	Work Station 1
O05	Retrieve cover template, place it on top of bolt heads and turn deck around.	Work Station 1	Work Station 1
O06	Retrieve 2 trucks and QR code scanner, scan trucks and place them onto deck.	Work Station 1	Work Station 1
O07	Pick 8 hardware nuts and place them on to bolts.	Work Station 1	Work Station 1
O08	Retrieve electric nut driver and screw nuts, then return electric nut driver.	Work Station 1	Work Station 1
O09	Look for needed wheels, retrieve QR code scanner and wheels. Scan wheel, pick wheel spacers and ball bearings, and place through each truck, wheel spacer, wheel and ball bearing for each side of the trucks.	Work Station 2	Work Station 2

O10	Pick truck nuts and place them onto each side of the trucks.	Work Station 2	Work Station 2
O11	Retrieve electric nut driver and screw truck nuts from on side, rotate skateboard, and fix other nuts, then return electric nut driver.	Work Station 2	Work Station 2
O12	Put away finished skateboard and return cover template.	Work Station 2	Work Station 2
O13	Apply customized torque to trucks.	Work Station 3	Work Station 3
O14	Install Connectivity Box	Work Station 4	Work Station 4

Table 5 - Assembly process description

Firstly, the assembly was tested and recorded in six assembly cycles. After a video analysis the assembly times of each operation were identified. Table 6 shows the results for the trial.

Element_i		Cycles					
Combined Code		1	2	3	4	5	6
P01O01	T	5	7	6	7	7	6
	L	5	7	6	7	7	6
P01O02	T	3	2	4	4	3	4
	L	8	9	10	11	10	10
P01O03	T	3	2	2	2	2	2
	L	11	11	12	13	12	12
P01O04	T	19	21	20	19	22	18
	L	30	32	32	32	34	30
P01O05	T	8	9	7	6	6	5
	L	38	41	39	38	40	35
P01O06	T	15	17	11	11	10	13
	L	53	58	50	49	50	48
P01O07	T	52	44	44	38	31	38
	L	105	102	94	87	81	86
P01O08	T	21	9	18	17	20	19
	L	126	111	112	104	101	105
P01O09	T	62	51	55	51	53	65
	L	188	162	167	155	154	170
P01O10	T	22	18	20	15	17	16
	L	210	180	187	170	171	186
P01O11	T	21	28	19	19	18	19
	L	231	208	206	189	189	205
P01O12	T	9	10	10	7	6	7
	L	240	218	216	196	195	212

T = Activity Time
L = Cumulative Cycle Time

Table 6 - Results of the video analysis

Based on the trials the standard cycle times were calculated based on the methods presented on the prior chapter, following the principles of time and motion studies. The standard cycle times determines how long the complete assembly process takes for a single skateboard by accounting for allowances and work rates. The results are presented in Table 7.

Operations 13 and 14 were left out as the additional tool and connectivity boxes for assembly were not ready by the time of the trials.

Element_i	Cycles						n_i	OT_i	RF_i	NT_i	f_i	Allowance	ST
Combined Code	1	2	3	4	5	6		[sec/cycle]	[%]	[sec/cycle]		[%]	[sec/cycle]
P01O01	5	7	6	7	7	6	6	6.33	100	6.33	1	15	7.45
P01O02	3	2	4	4	3	4	6	3.33	100	3.33	1	15	3.92
P01O03	3	2	2	2	2	2	6	2.17	100	2.17	1	10	2.41
P01O04	19	21	20	19	22	18	6	19.83	100	19.83	1	10	22.04
P01O05	8	9	7	6	6	5	6	6.83	100	6.83	1	10	7.59
P01O06	15	17	11	11	10	13	6	12.83	100	12.83	1	10	14.26
P01O07	52	44	44	38	31	38	6	41.17	100	41.17	1	10	45.74
P01O08	21	9	18	17	20	19	6	17.33	100	17.33	1	15	20.39
P01O09	62	51	55	51	53	65	6	56.17	105	58.98	1	15	69.38
P01O10	22	18	20	15	17	16	6	18.00	100	18.00	1	10	20.00
P01O11	21	28	19	19	18	19	6	20.67	100	20.67	1	15	24.31
P01O12	9	10	10	7	6	7	6	8.17	100	8.17	1	10	9.07
Total Standard Cycle Time													246.57

n = non-outlier observations

OT = average observed activity time (without outliers)

RF = Rating Factor (greater than 100%, means the worker is working at a higher rate, than others)

NT = Normal Time

f = frequency of observed activity in a work unit

Allowance = sum of all work tolerances including, personal time, fatigue and delays.

ST = Standard Time

Table 7 - Calculation of Standard Times of the Assembly Process

To breakdown the activities into distinct workstations a target for the cycle times was set for the factory, namely, that the complete assembly process has to have a finished skateboard every 2 minutes. By defining this target and the lack of resources to establish parallel assembly flows it was decided to implement a sequential flow in four different workstations.

Workstation 1 accounts for all processes until assembling the trucks on the skateboard. In Workstation 2 the skateboard wheels are assembled, while in Workstations 3 and 4 we have the application of the customized torque on the truck and the installation of the connectivity box, respectively. The operations within each workstation were broken down to fit the desired time target as seen on Table 8, with the activity breakdown per workstation and in Figure 18, where line balancing becomes evident graphically.

Element_i Combined Code	Work Station	ST [sec/cycle]	
P01O01	Work Station 1	7.45	
P01O02	Work Station 1	3.92	
P01O03	Work Station 1	2.41	
P01O04	Work Station 1	22.04	
P01O05	Work Station 1	7.59	
P01O06	Work Station 1	14.26	
P01O07	Work Station 1	45.74	
P01O08	Work Station 1	20.39	123.80
P01O09	Work Station 2	69.38	
P01O10	Work Station 2	20.00	
P01O11	Work Station 2	24.31	
P01O12	Work Station 2	9.07	122.77
P02O13	Work Station 3	20.00	
P02O14	Work Station 3	100.00	120.00
P02O15	Work Station 4	120.00	120.00

Table 8 - Line Balancing of the Assembly Process

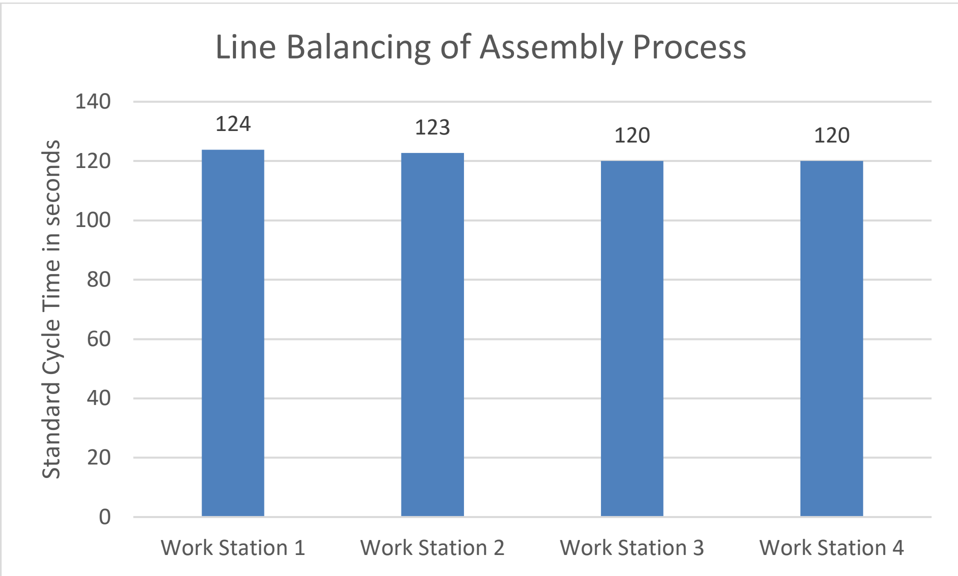


Figure 20 - Result of the Line Balancing

Comparing the original process and the improvement process, while choosing identical activities within each workstation it becomes evident, that the bottleneck of the original process shows a cycle time of 155 seconds, while the improved bottle neck shows a cycle time of 124 seconds, a 31 second improvement.

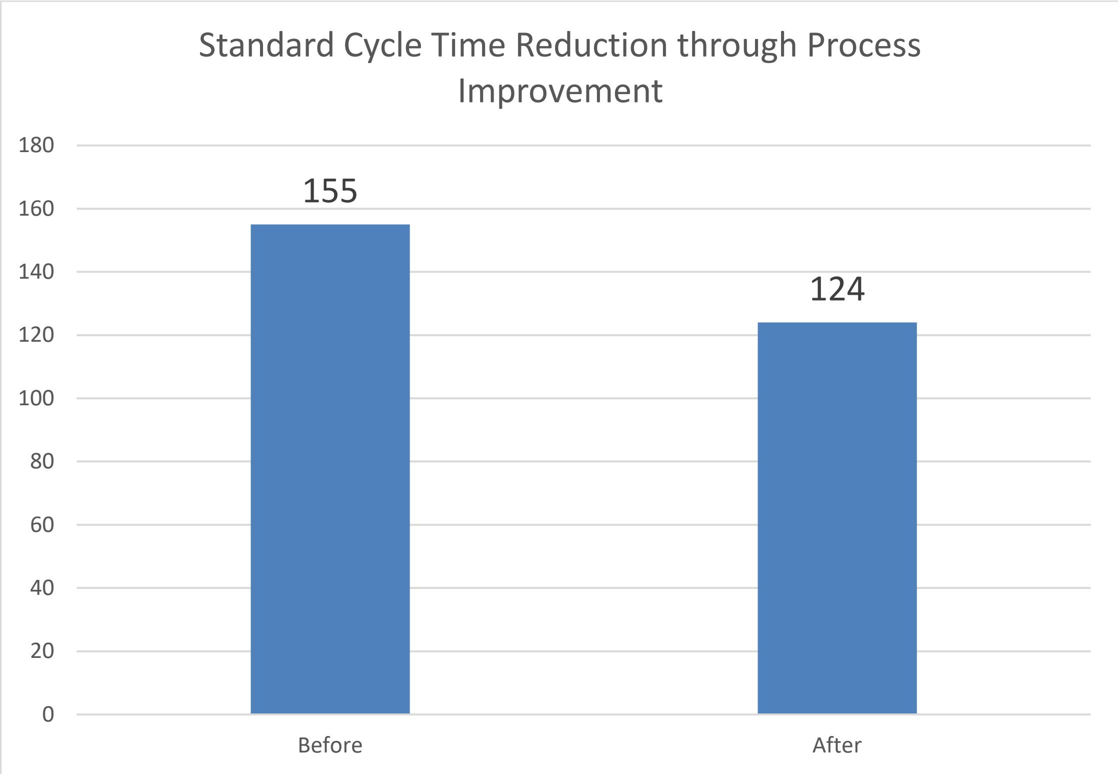


Figure 21 - Standard Cycle Times before and after Process Improvement

4.2 Application of SLP

The application of the SLP is separated into several steps already presented in Chapter 3.2. Firstly, the current factory layout and its components are presented, then, the distances and moved weights between each component are established to start the systematic layout planning.

Afterwards the P-Q Chart is created based ordered by the product distance x weight to create the From-To chart. Based on the From-To chart the flow relationship diagram is build and lastly the final allocation of the components within the new layout.

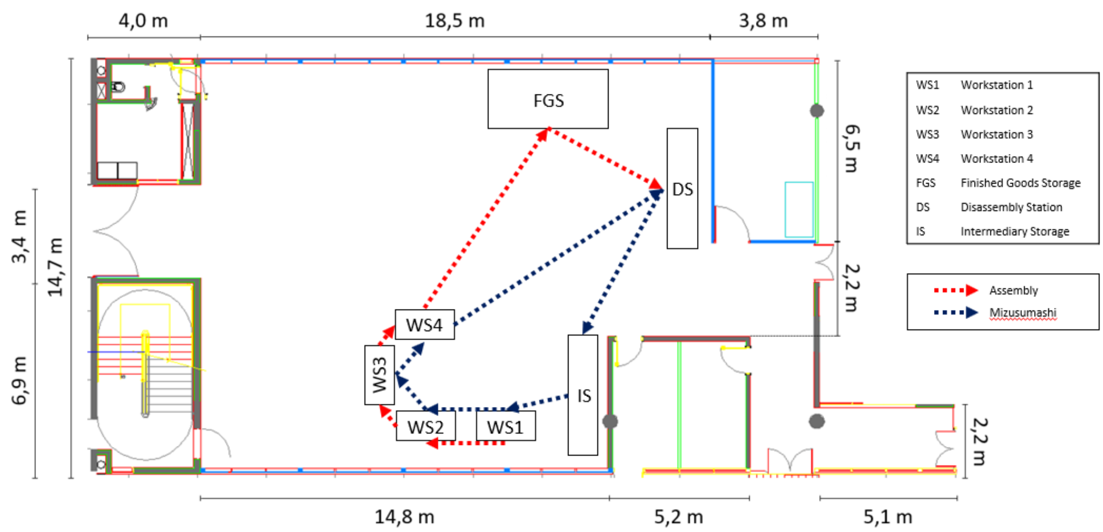


Figure 22 - Current Factory Layout

Figure 22 shows the current layout, the current assembly and mizusumashi process flow and the integral parts of the factory are presented below, while *Appendix B* shows pictures of all the contents within each of the particular layout components:

- Workstation 1 (WS1): Assembly workstation for assembling the trucks onto the skateboard.
- Workstation 2 (WS2): Assembly workstation for assembling the wheels onto the trucks.
- Workstation 3 (WS3): Customization station, in which a predefined torque is applied to the trucks.
- Workstation 4 (WS4): Assembly workstation for assembling the connectivity box.
- Finished Goods Storage (FGS): Storage unit for the finished skateboards.
- Disassembly Station (DS): Disassembly station for finished skateboards. Since the *Fábrica do Futuro* is a learning factory, the assembled goods are not sold the materials are reutilized for the assembly of new skateboards.
- Intermediary Storage (IS): Storage unit for components of the skateboard
- Assembly process flow (red line): Shows the flow of assembled part between stations. Note that no materials need to be picked by workers at storage units. This is done by the mizusumashi.

- Mizusumashi process flow (blue line): Shows the flow of the mizusumashi, which transports the goods between storage units for material replenishment in all workstations. The mizusumashi is a cart with different repositories for each skateboard component and replenishes materials in a multiple of cycle times of each workstation.

To create the From-To chart it is necessary to compile all the moved weights and distances in each of the utilized routes. Figure 22 maps all utilized routes for the assembly and mizusumashi process flows. The weights of each transported component and the utilized routes for each transported good is presented in *Appendix C – Mapping Material Needs in Routes.*

The result of this analysis are the material flows for both of the processes, including the product distance x weight shown in the figure below.

	Assembly				
	WS1 - WS2	WS2 - WS3	WS3 - WS4	WS4 - FGS	FGS - DS
Distance [m]	0.7	1.4	1.4	7.4	4.7
Weight Transported per Skateboard [g]	2095.0	2508.0	2509.0	2727.0	2727.0
Weight Transported per Shift [kg]	209.5	250.8	250.9	272.7	272.7
Product Distance - Weight	141.7	339.3	339.5	2029.2	1291.3

	Mizusumashi					
	IS - WS1	WS1 - WS2	WS2 - WS3	WS3 - WS4	WS4 - DS	DS - IS
Distance [m]	2.7	0.7	1.4	1.4	8.8	6.1
Weight Transported per Skateboard [g]	2727.0	632.0	219.0	218.0	0.0	2727.0
Weight Transported per Shift [kg]	272.7	63.2	21.9	21.8	0.0	272.7
Product Distance - Weight	737.9	42.8	29.6	29.5	0.0	1660.3

Table 9 - Material Flow between Areas

The From-To chart of flow relationships summarize the findings of the analysis in a single chart for both processes aggregating the weights of each route. The result is shown in Table 10 and the classification of each route in the vowel letter classification follows in Table 11, while the results are plotted into a graph in Figure 23.

From - To	IS	WS1	WS2	WS3	WS4	FGS	DS
IS		737.9					
WS1			184.5				
WS2				368.9			
WS3					368.9		
WS4						2029.2	0
FGS							1291.3
DA	1660.3						

Table 10 - From-To Chart of Flow Relationships

#	Route	kg x m	%i	Classification
1	WS4 - FGS	2029.2	4%	A
2	DS - IS	1660.3	7%	E
3	FGS - DS	1291.3	11%	I
4	IS - WS1	737.9	14%	I
5	WS2 - WS3	368.9	18%	O
6	WS3 - WS4	368.9	21%	O
7	WS1 - WS2	184.5	25%	O
8	WS4 - DS	0.0	29%	U

Table 11 - Route Classification using the Vowel-Letter Classification

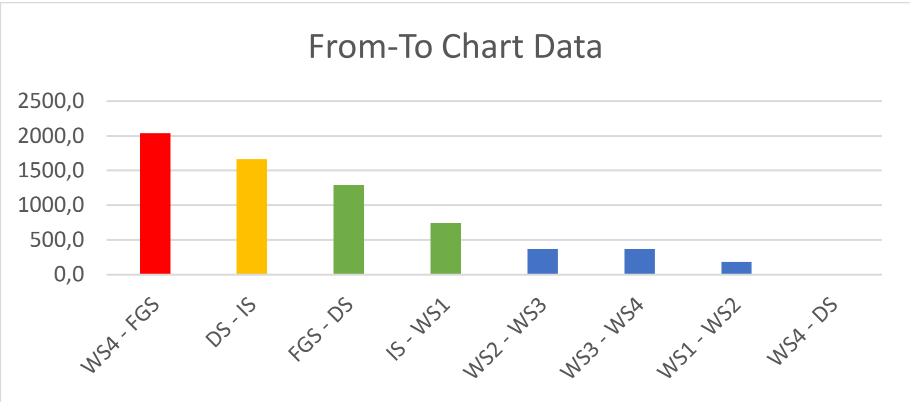


Figure 23 - From-To Chart Data according to Vowel-Letter Classification

The next step in the SLP methodology requires the creation of the flow and activity relationship diagram based on the rules presented in chapter 3.2.3. Each vowel letter classified route receives a predefined distance to be connected to each route. The result of fitting the fictitious distances between each layout component is presented in Figure 24.

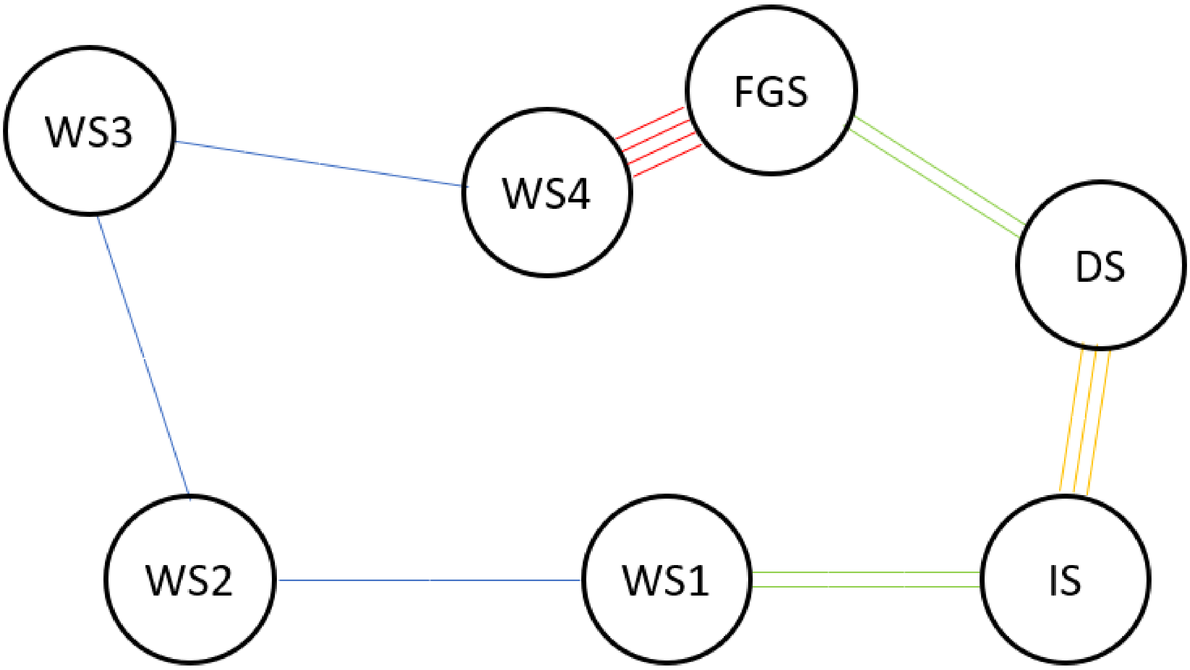


Figure 24 - Flow and Activity Relationship Diagram

Inserting the insights of the flow and activity relationship diagram into the factory space results in the optimized factory layout presented in Figure 23

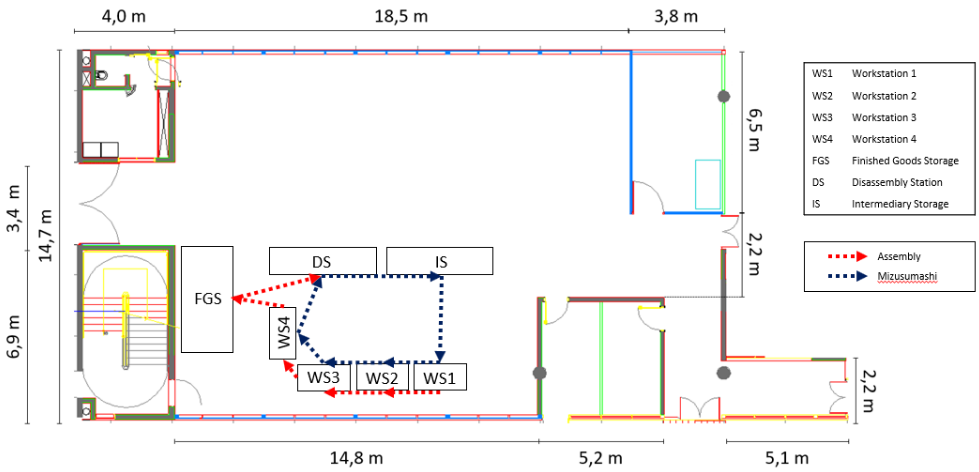


Figure 25 - Optimized Layout

The results of applying the SLP methodology is visible in several ways:

- Table 12 shows the distances between each layout component were either reduced or remained the same
- Figure 26 shows that the product distance x weight reduced in all but one route, while also remaining the same for one single route
- Figure 27 shows that the aggregated total product distance x weight reduced 42% using the SLP methodology

	Assembly				
	WS1 - WS2	WS2 - WS3	WS3 - WS4	WS4 - FGS	FGS - DS
Distance before [m]	0.7	1.4	1.4	7.4	4.7
Distance after [m]	0.5	0.5	1.4	2.5	3.2

	Mizusumashi					
	IS - WS1	WS1 - WS2	WS2 - WS3	WS3 - WS4	WS4 - DS	DS - IS
Distance before [m]	2.7	0.7	1.4	1.4	8.8	6.1
Distance after [m]	3.0	0.5	0.5	1.4	5.9	3.0

Table 12 - Route Distances after Optimization

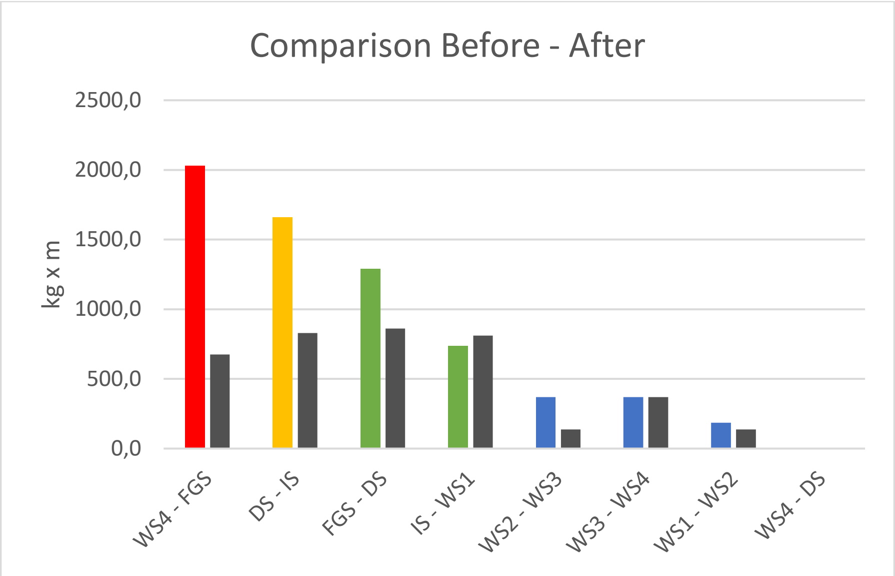


Figure 26 - Result of SLP Application

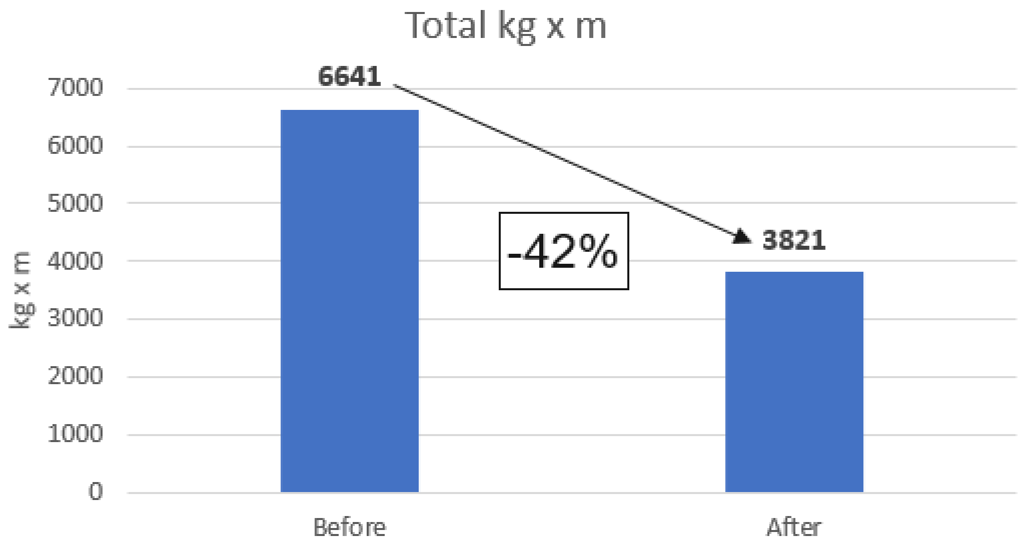


Figure 27 - Result of SLP Application

5 Conclusion

With the conclusion of this work the *Fábrica do Futuro* has a complete and ready layout for assembling skateboards in its new assembly line.

The time and motion study clearly defined all the needed operations for assembly in each workstation and successfully reduced standard cycle times by 31 seconds (20%). Systematic layout planning enabled a 2820 (42%) reduction of the product distance weight, for the whole system including the assembly flow and the *mizusumashi* process flow.

All the equipments and components for the assembly line were bought, installed and tested, while custom assembly tools were designed, prototyped and tested. Therefore, this work concludes with a finished assembly line for the *Fábrica do Futuro*, ready for additional implementation to reach its potential as an industry 4.0 and logistics 4.0 beacon for research in Brazil.

The coming months are going to be used to enhance the assembly line with several technology innovations.

- Additive manufacturing of spare parts for skateboard directly at the factory site. The goal is to reduce logistics costs, while also making personalized components for visitors of the factory
- Computer vision and artificial intelligence will support the assembly of workstation 2. The goal is to show workers on a screen or through augmented reality classes, which wheels they should assemble into each truck. This technology will enable the identification of assembly line mistakes in a poka yoke concept and, thus, making sure no assembly mistakes leave for the next workstation
- Drone delivery of the connectivity box is seen as a possibility to move small weight components with great added value to the product through flexible drone deliveries. The delivery will be performed within the campus, as the connectivity box is manufactured in another research institute and should show how drone delivery might be an alternative for flexible small lot deliveries.
- Digital twin of the factory through IoT will create a digital duplicate of the whole *Fábrica do Futuro* through low cost sensors applied to different parts of the skateboard. The use of such digital twin is the real-time observation of the factory, which can be used for advanced analytics once a large enough dataset is created.

Those are a few applications of industry 4.0 and logistics 4.0 technologies, that will be implemented at the *Fábrica to Futuro* in its road to a true learning factory of the future.

Appendix

Appendix A – Operations Analysis Checklist

The following checklist can assist an engineer while analyzing an operation (Barnes 1980):

<u>I) Materials:</u>

1. Can cheaper material be substituted?
2. Is the material uniform and in proper condition when brought to the operator?
3. Is the material of proper size, weight, and finish for most economical use?
4. Is the material utilized to the fullest extent?
5. Can some use be found for scrap and rejected parts?
6.* Can the number of storages of material and of parts in process be reduced?

<u>II) Materials Handling:</u>

1. Can the number of times the material is handled be reduced?
2. Can the distance moved be shortened?
3. Is the material received, moved, and stored in suitable containers?
4. Are there delays in the delivery of material to the operator?
5. Can the operator be relieved of handling materials by the use of conveyors?
6. Can backtracking be reduced or eliminated?
7. Will a rearrangement of the layout or combining of operations make it unnecessary to move the material?

<u>III) Tools, Jigs, and Fixtures:</u>

1. Are the tools the best kind for this work?
2. Are the tools in good condition?
3. If metal-cutting tools, are the cutting angles of the tools correct and are they ground in a centralized tool-grinding department?
4. Can tools or fixtures be changed so that less skill is required to operate?
5. Are both hands occupied by productive work in using the tools or fixtures?
6. Can "slide feeds," "ejectors," "holding devices," etc., be used?
7. Can an "engineering change" be made to simplify the design?

<u>IV) Machine:</u>

A. Setup:

1. Should the operator set up his machine?

2. Can the number of setups be reduced by proper lot sizes?

3. Are drawings, tools, and gauges obtained without delay?

4. Are there delays in inspecting first pieces produced?

B. Operation:

1. Can the operation be eliminated?

2. Can the work be done in multiple?

3. Can the machine speed or feed be increased?

4. Can an automatic feed be used?

5. Can the operation be divided into two or more short operations?

6. Can two or more operations be combined into one? Consider the effect of combinations on the training period.

7. Can the sequence of the operation be changed?

8. Can the amount of scrap and spoiled work be reduced?

9. Can the part be pre-positioned for the next operation?

10. Can interruptions be reduced or eliminated?

11. Can an inspection be combined with an operation?

12. Is the machine in good condition?

V) Operator:

1. Is the operator qualified mentally and physically to perform this operation?

2. Can unnecessary fatigue be eliminated by a change in tools, fixtures, layout, or working conditions?

3. Is the base wage correct for this kind of work?

4. Is supervision satisfactory?

5. Can further instruction improve the operator's performance?

VI) Working Conditions:

1. Is the light, heat, and ventilation satisfactory on the job?

2. Are washrooms, lockers, restrooms, and dressing facilities adequate?

3. Are there any unnecessary hazards involved in the operation?

4. Is provision made for the operator to work in either a sitting or a standing position?

5. Are the length of the working day and the rest periods set for the maximum economy?

6. Is good housekeeping maintained throughout the plant?

Appendix B – Layout components

Figure 28 - Intermediary storage

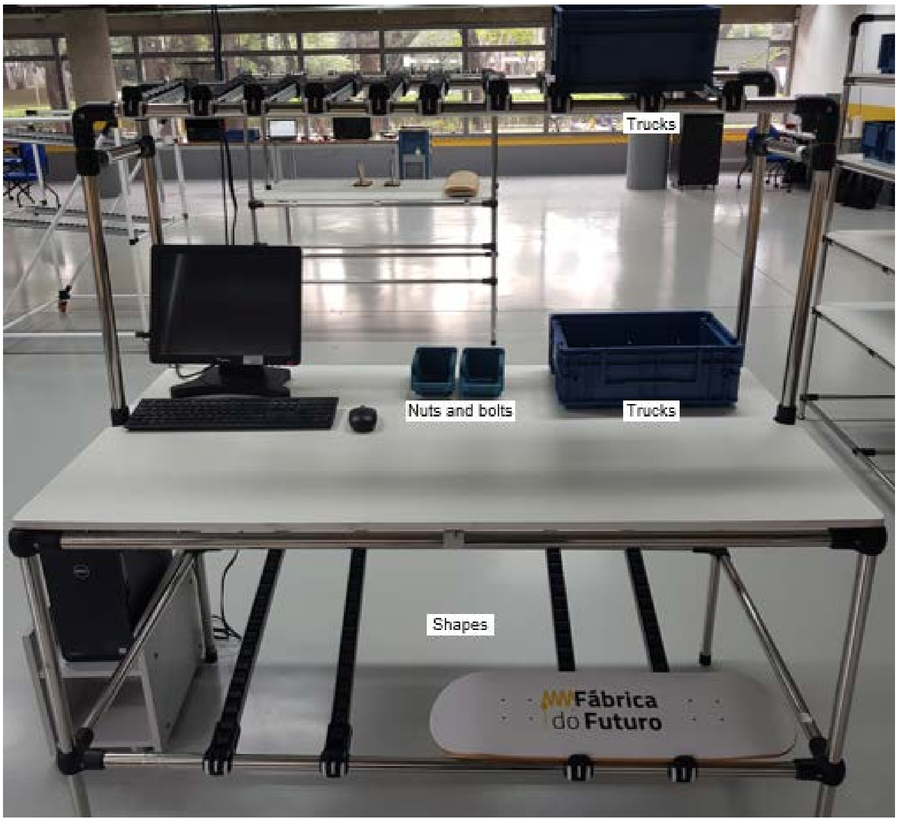


Figure 29 - Workstation 1

Figure 30 - Workstation 2

Figure 31 - Disassembly station

Figure 32 - Mizusumashi

Appendix C – Mapping Material Needs in Routes

	Part Weight [g]	Parts/Set	Set Weight [g]	Assembly				
				WS1 - WS2	WS2 - WS3	WS3 - WS4	WS4 - FGS	FGS - DS
Deck	1359	1	1359	1	1	1	1	1
Hardware Bolt	3	8	24	1	1	1	1	1
Truck	350	2	700	1	1	1	1	1
Hardware Nut	1.5	8	12	1	1	1	1	1
Wheel Spacer	6.5	4	26	0	1	1	1	1
Ball Bearing	10	8	80	0	1	1	1	1
Wheel	75	4	300	0	1	1	1	1
Truck Nut	1.75	4	7	0	1	1	1	1
Custom Sticker	1	1	1	0	0	1	1	1
IoT Box Bolts	3	4	12	0	0	0	1	1
IoT Box	200	1	200	0	0	0	1	1
IoT Box Nuts	1.5	4	6	0	0	0	1	1

	Part Weight [g]	Parts/Set	Set Weight [g]	Mizusumashi					
				IS - WS1	WS1 - WS2	WS2 - WS3	WS3 - WS4	WS4 - DS	DS - IS
Deck	1359	1	1359	1	0	0	0	0	1
Hardware Bolt	3	8	24	1	0	0	0	0	1
Truck	350	2	700	1	0	0	0	0	1
Hardware Nut	1.5	8	12	1	0	0	0	0	1
Wheel Spacer	6.5	4	26	1	1	0	0	0	1
Ball Bearing	10	8	80	1	1	0	0	0	1
Wheel	75	4	300	1	1	0	0	0	1
Truck Nut	1.75	4	7	1	1	0	0	0	1
Custom Sticker	1	1	1	1	1	1	0	0	1
IoT Box Bolts	3	4	12	1	1	1	1	0	1
IoT Box	200	1	200	1	1	1	1	0	1
IoT Box Nuts	1.5	4	6	1	1	1	1	0	1

Table 13 - Flow Relationships between Areas

References

Abele, E.; Cachay, J.; Wennemer, J. (2011): Personalmanagement-Kompetenzentwicklung und Führung bei Verbesserungsprozessen in der Produktion. In *Industrie Management* 27 (4), p. 14.

Abele, Eberhard; Metternich, Joachim; Tisch, Michael; Chryssolouris, George; Sihn, Wilfried; ElMaraghy, Hoda et al. (2015): Learning factories for research, education, and training. In *Procedia CIRP* 32, pp. 1–6.

Alicke, Knut; Rachor, Jürgen; Seyfert, Andreas (2016): Supply Chain 4.0 - the next-generation digital supply chain.

American Society of Mechanical Engineers (1947): Operation and flow Process Charts. New York.

Arnold, Dieter; Furmans, Kai; Isermann, Heinz; Kuhn, Axel; Tempelmeier, Horst (2008): Handbuch logistik: Springer.

Attaran, Mohsen (2017): Additive manufacturing: the most promising technology to alter the supply chain and logistics. In *Journal of Service Science and Management* 10 (3), pp. 189–205.

Azuma, Ronald T. (1997): A survey of augmented reality. In *Presence: Teleoperators & Virtual Environments* 6 (4), pp. 355–385.

Barnes, Ralph M. (1980): Motion and time study. Design and measurement of work. 7. ed. New York: Wiley.

Barreto, L.; Amaral, A.; Pereira, T. (2017): Industry 4.0 implications in logistics: an overview. In *Procedia Manufacturing* 13, pp. 1245–1252. DOI: 10.1016/j.promfg.2017.09.045.

Bosworth, Seymour; Kabay, Michel E. (2002): Computer security handbook: John Wiley & Sons.

Chan, Brodie; Guan, Hong; Jo, Jun; Blumenstein, Michael (2015): Towards UAV-based bridge inspection systems: A review and an application perspective. In *Structural Monitoring and Maintenance* 2 (3), pp. 283–300.

Chen, Min; Mao, Shiwen; Liu, Yunhao (2014): Big data: A survey. In *Mobile networks and applications* 19 (2), pp. 171–209.

Christidis, Konstantinos; Devetsikiotis, Michael (2016): Blockchains and smart contracts for the internet of things. In *Ieee Access* 4, pp. 2292–2303.

Cirulis, Arnis; Ginters, Egils (2013): Augmented reality in logistics. In *Procedia Computer Science* 26, pp. 14–20.

Daecher, Andy; Cotteleer, Mark; Holdowsky, Jonathan (2018): The Internet of Things: A technical primer. Available online at https://www2.deloitte.com/insights/us/en/focus/internet-of-things/technical-primer.html.

ElMaraghy, Hoda; AlGeddawy, T.; Azab, A.; ElMaraghy, Waguih (2012): Change in manufacturing–research and industrial challenges. In : Enabling manufacturing competitiveness and economic sustainability: Springer, pp. 2–9.

ElMaraghy, Hoda A. (2009): An Introduction. In : Changeable and reconfigurable manufacturing systems: Springer, pp. 3–24.
Fleisch, E. (2010): What is the Internet of things? An Economic Perspective; Auto-ID Labs White Paper WP-BIZAPP-053. In *Electronic text at http://www. autoidlabs. org/uploads/media/AUTOIDLABS-WP-BIZAPP-53. pdf.*
Gaus, Tim; Olsen, Ken; Deloso, Mike (2018): Synchronizing the digital supply network. Using artificial intelligence for supply chain planning.
Groover, Mikell P. (2007): Automation, production systems, and computer-integrated manufacturing: Prentice Hall Press.
Grundig, Claus-Gerold (2014): Fabrikplanung: Planungssystematik-Methoden-Anwendungen: Carl Hanser Verlag GmbH Co KG.
Hashem, Ibrahim Abaker Targio; Yaqoob, Ibrar; Anuar, Nor Badrul; Mokhtar, Salimah; Gani, Abdullah; Khan, Samee Ullah (2015): The rise of "big data" on cloud computing: Review and open research issues. In *Information systems* 47, pp. 98–115.
Hofmann, Erik; Rüsch, Marco (2017): Industry 4.0 and the current status as well as future prospects on logistics. In *Computers in Industry* 89, pp. 23–34. DOI: 10.1016/j.compind.2017.04.002.
Holtkamp, Bernhard; Steinbuss, Sebastian; Gsell, Heiko; Loeffeler, Thorsten; Springer, Ulrich (Eds.) (2010): Towards a logistics cloud: IEEE.
Jakob, Sabine; Schulte, Axel T.; Sparer, Dominik; Koller, Roman; Henke, Michael (2018): Blockchain und Smart Contracts: Effiziente und sichere Wertschoepfungsnetzwerke. With assistance of Michael ten Hompel, Michael Henke, Uwe Clausen.
Jeschke, Sabina; Brecher, Christian; Meisen, Tobias; Özdemir, Denis; Eschert, Tim (2017): Industrial internet of things and cyber manufacturing systems. In : Industrial Internet of Things: Springer, pp. 3–19.
Kayikci, Yasanur (2018): Sustainability impact of digitization in logistics. In *Procedia Manufacturing* 21, pp. 782–789. DOI: 10.1016/j.promfg.2018.02.184.
Kettner, Hans; Schmidt, Jürgen; Greim, Hans-Robert (1984): Leitfaden der systematischen Fabrikplanung: Hanser München.
Knofius, Nils; van der Heijden, Matthieu C; Zijm, Willem H. M. (2016): Selecting parts for additive manufacturing in service logistics. In *Journal of manufacturing technology management* 27 (7), pp. 915–931.
Laurila, Juha K.; Gatica-Perez, Daniel; Aad, Imad; Bornet, Olivier; Do, Trinh-Minh-Tri; Dousse, Olivier et al. (2012): The mobile data challenge: Big data for mobile computing research.
Lourenço, André; Marques, Francisco; Mendonça, Ricardo; Pinto, Eduardo; Barata, José (Eds.) (2016): On the design of the ROBO-PARTNER Intra-factory Logistics Autonomous Robot: IEEE.

Muller, Egon; Horbach, Sebastian; Ackermann, Jorg (2008): Integrative planning and design of logistics structures and production plants in Competence-cell-based networks. In *International Journal of Services Operations and Informatics* 3 (1), pp. 40–52.
Muther, Richard (1973): Systematic Layout Planning (658.5 m8).
Oeser, Gerald (2018): Logistik 4.0. Available online at https://wirtschaftslexikon.gabler.de/definition/logistik-40-54203/version-329884.
Pawellek, G. (2007): Produktionslogistikâ€"Grundlagen, Methoden, Tools: Carl Hanser Verlag, Leipzig.
Pawellek, Günther (2014): Ganzheitliche Fabrikplanung: Grundlagen, Vorgehensweise, EDV-Unterstützung: Springer-Verlag.
Rajkumar; Lee; Sha; Stankovic (Eds.) (2013): Parallel scheduling for cyber-physical systems: Analysis and case study on a self-driving car. Proceedings of the ACM/IEEE 4th international conference on cyber-physical systems: ACM.
Reif, Rupert; Walch, Dennis (2008): Augmented & Virtual Reality applications in the field of logistics. In *The Visual Computer* 24 (11), pp. 987–994.
Renner, Ryan; Cotteleer, Mark; Holdowsky, Jonathan (2018): Cognitive technologies: A technical primer. Available online at https://www2.deloitte.com/insights/us/en/focus/cognitive-technologies/technical-primer.html.
San, Khin Thida; Mun, Sun Ju; Choe, Yeong Hun; Chang, Yoon Seok (Eds.) (2018): Uav delivery monitoring system: EDP Sciences (151).
Schwerdtfeger, Bjorn; Klinker, Gudrun (Eds.) (2008): Supporting order picking with augmented reality: IEEE.
Shingo, Shigeo (1986): Zero quality control: source inspection and the poka-yoke system: CRC Press.
Slack, Nigel; Brandon-Jones, Alistair; Johnston, Robert B. (2013): Operations management. Seventh edition. Harlow: Pearson (Always learning).
Szabo, Nick (1994): Smart contracts. In *Unpublished manuscript.*
Tjahjono, B.; Esplugues, C.; Ares, E.; Pelaez, G. (2017): What does Industry 4.0 mean to Supply Chain? In *Procedia Manufacturing* 13, pp. 1175–1182. DOI: 10.1016/j.promfg.2017.09.191.
Tsugawa, Sadayuki; Jeschke, Sabina; Shladover, Steven E. (2016): A Review of Truck Platooning Projects for Energy Savings. In *IEEE Trans. Intelligent Vehicles* 1 (1), pp. 68–77.
Ungeheuer, Udo (1986): Produkt-und Montagestrukturierung: Methodik zur Planung e. anforderungsgerechten Produkt-u. Montagestruktur für komplexe Erzeugnisse d. Einzel-u. Kleinserienproduktion: VDI-Verlag.
Wagner, Ulf; AlGeddawy, Tarek; ElMaraghy, Hoda; MŸller, E. (2012): The state-of-the-art and prospects of learning factories. In *Procedia CIRP* 3, pp. 109–114.
Wang, Shiyong; Wan, Jiafu; Di Li; Zhang, Chunhua (2016): Implementing smart factory of industrie 4.0: an outlook. In *International Journal of Distributed Sensor Networks* 12 (1), p. 3159805.

Wiendahl, Hans-Peter (2014): Betriebsorganisation für Ingenieure: Carl Hanser Verlag GmbH Co KG.

Wiendahl, Hans-Peter; Reichardt, Jürgen; Nyhuis, Peter (2014): Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten: Carl Hanser Verlag GmbH Co KG.

Witkowski, Krzysztof (2017): Internet of Things, Big Data, Industry 4.0 – Innovative Solutions in Logistics and Supply Chains Management. In *Procedia Engineering* 182, pp. 763–769. DOI: 10.1016/j.proeng.2017.03.197.

Wolfert, Sjaak; Ge, Lan; Verdouw, Cor; Bogaardt, Marc-Jeroen (2017): Big Data in Smart Farming – A review. In *Agricultural Systems* 153, pp. 69–80. DOI: 10.1016/j.agsy.2017.01.023.

Wrycza, Philipp (2019): DelivAIRy. Was ist DelivAIRy? Available online at https://www.iml.fraunhofer.de/de/abteilungen/b1/verpackungs_und_handelslogistik/forschungsprojekte/delivairy.html.

Zhang, Xu; Scholz, Michael; Reitelshöfer, Sebastian; Franke, Jörg (Eds.) (2018): An autonomous robotic system for intralogistics assisted by distributed smart camera network for navigation: IEEE.