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Adaptive Smart Assembly Concept in e-Mobility: A Research Direction

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Abstract

Achieving high total volume, high variety batch size production can be quite expensive. In this vision paper, the methodology of achieving this at low costs and the available technologies in the field of e-mobility production are described. The focus of this research lies in high adaptive and cognitive aspects in the assembly. To match the high flexibility of a Flexible Manufacturing System while considering costs, a use case of an e-axle assembly is being done. E-axle is chosen due to the ongoing electrification of mobility as the demand of mass production is low. Hence, a solution for implementing a set of methodologies for an adaptive manufacturing system with respect to assembly and implementation efforts is shown. A LoPA (Level of Practical Application) matrix is presented of all the possible adaptive technologies that are feasible to implement in the e-assembly line.

Keywords: Adaptive Smart Assembly, e-Mobility, Cognitive Production, High Variety Batch Production, Level of Practical Application (LoPA).

1. Introduction

In the last century, researches were focused on low-cost products and achieving them with mass production with highly efficient Dedicated Manufacturing Systems (DMS). These are used for manufacturing high quantities of the similar product at low throughput times. Hence, DMS are fixed and have a monotonous sequence of steps. If an additional process step for one part is required, the efficiency of this system decreases significantly. (Ko, Hu, & Huang, 2005).

Now given the shift in recent years, researches are focusing on Flexible Manufacturing Systems (FMS) to keep pace with the ongoing mass customization. Flexible Manufacturing Systems are versatile and adaptive to variety of products. But, the complexity of FMS and costs of implementing such a system is quite high. Also, FMS has a lower productivity compared to DMS as the production steps are not conducted simultaneously (Abou-El-Hossein, Theron, & Ghobashy, 2015). Thus, an advantage of FMS would be that it has a vast amount of flexible automation. It is also noted that majority of users in the industry are not satisfied with the FMSs because of variety of problems including lack of reconfigurability as a result of their fixed capacities and functionalities (Mehrabi, Ulsoy, Koren, & Heytler, 2002). These are the two opposed types of manufacturing systems.

One of the challenges of the 21st century is the dynamic interaction between the distinct manufacturing processes and adaptability machines developed by engineers (Sugiarto, Axenie, & Conradt, 2016). The variances in vehicle types of electromobility (e-mobility) are high and the batch size is low, which in turn makes the manufacturing and assembling costs higher (Marcel Schwartz, Dipl.-W irt.-Ing. Dominik Kolz, & Katharina Heeg, 2016). Thus, the manufacturers are dependent to match this high flexibility and variety. To match the high flexibility of an FMS system while considering costs, a use case of an e-axle assembly is being done. E-axle is considered as the market maturity of the electric vehicle sector is low ("Electric Car (Market) Data," 2018). Hence, the goal would be to implement a set of smart technologies for an adaptive assembly system with respect to e-mobility. Also, the focus is to achieve the right balance between the machines and humans to make the assembly process simpler, faster and less expensive by combining the proven methodologies.

This paper outlines the planned research in terms of investigating how the aforementioned adaptivity can be achieved in an e-axle assembly. To do so, the existing process design of the assembly is analyzed to identify the technological gaps. Further, to bridge this disparity, requirements of adaptive assembly system are described. Additionally, the research gap is presented by combining the benefits of these concepts and presenting the various technologies. Finally, with the help of verification models, the paper draws an outline of expected results.

2. Process Analysis and Requirements

2.1 Existing Process Design

To develop an adaptive assembly system the process sequence is defined. To do so, the assembly sequence for an existing specific e-axle (as illustrated in **Figure 1**) is analyzed first (short overview).

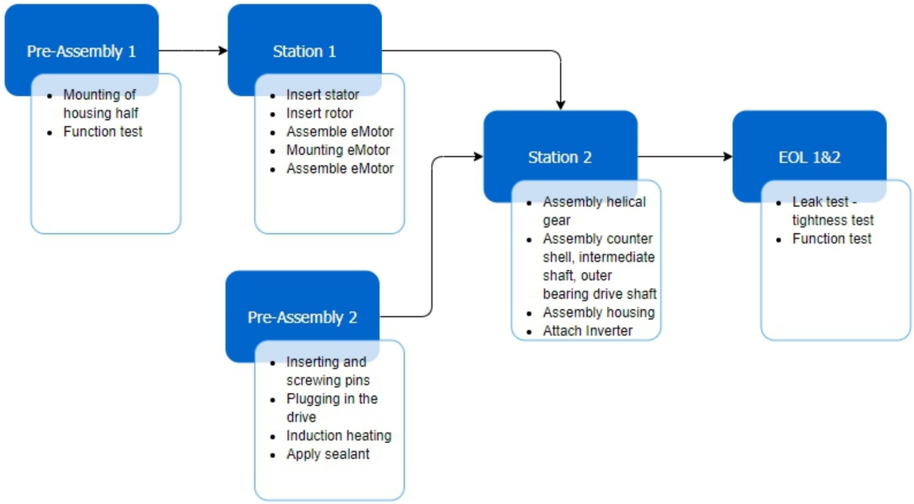


Fig. 1. Structure of the e-axle assembly.

The assembly sequence is an ideal case of flow or series assembly. All the parts are transported to the pre-assembly station except for the rotor and stator, which are supplied to station 1. All the tasks are performed manually. There are two end of line testing stations (EOL 1 & 2) which have a machine for testing the final run of the axle. The yearly requirement is to assemble 4000 axles, thereby the daily output would be roughly 20 axles considering 205 working days. However, additional e-axles would be assembled on this assembly line. Thus, the aim is to make the assembly line adaptive thereby reducing the assembly time for this specific e-axle.

Since the yearly output of an e-axle is low, implementing a fully automatic assembly would not be feasible and cost effective. As described in a case study done in (Wiendahl et al., 2007), implementing an automated system for lower throughput per day can be expensive. **Figure 2** describes the summary relation between output volume and costs based on (Wiendahl et al., 2007).

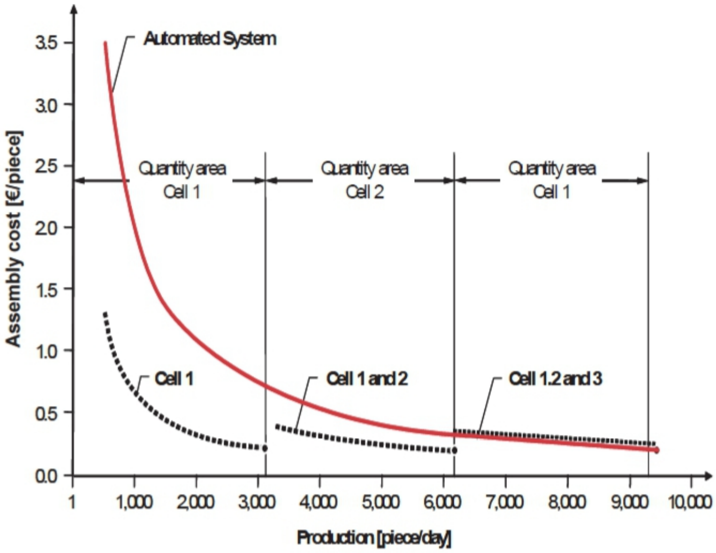


Fig. 2. Assembly cost for automated assembly versus hybrid assembly cells (Wiendahl et al., 2007).

2.2 Requirements of Adaptive Assembly

After the thorough literature review phase, four main concepts were derived (Migration manufacturing, Holonic Manufacturing System, Reconfigurable Manufacturing System, Cognitive Factory – HMI). These concepts focus on one or more core areas of an assembly plant along with their KPIs (Key Performance Indicators). For example, if "throughput" is considered, the concept of HMS, RMS, and Cognitive Factory achieve this KPI. Likewise, the concept of Migration Manufacturing focusses on the KPI: "Area" and so on. These KPIs forms the basis as a requirement of an adaptive assembly. Table 1 shows these 4 concepts, core areas and respective KPIs. Marked "**x**" indicates that the concept targets a specific core area.

Table 1. Concepts, core areas and their KPIs.

		Concepts			
Core Area	**Key Perfromance Indicators (KPIs)**	**Migration Manufacturing**	**Holonic Manufacturing System (HMS)**	**Reconfigurable Manufacturing System (RMS)**	**Cognitive Factory – HMI**
Layout	Area (m^2), design of layout	×			
Process	Throughput, Overall Equipmen		×	×	×

	t Efficiency (OEE), quality				
Machine	Cost, throughput, quality, performance		×	×	×
Logistics	Time, inventory		×		

3. State of the Art

As shown in table above, the concepts focus on 4 main core areas of the assembly plant which in turn has several KPIs. These concepts are selected as they are most suitable for ramp-up of high variety, low batch size assembly. They are explained below in a nutshell.

Migration Manufacturing. The number of variants of each e-axle are increasing considerably with slight variations. Migration manufacturing helps with a method that can manufacture these different parts on the same assembly line (Meichsner, 2008). The use-case of migration manufacturing with meandering technique has been explained in (Meichsner, 2008).

The assembly process has base stations and the additional tasks (such as welding) that are required for some products can be implemented by creating a loop through the stations. In other words, implementing an additional small line where the input and output of the line is the same station. Inside this loop stations, are worker(s) which perform the additional task required for the product/part. A part which does not require this additional task moves forward through the main line, and the part which requires it moves into the loop line. (Meichsner, 2008)

Holonic Manufacturing System. Holonic Manufacturing System (HMS), is a concept used for increasing the flexibility, agility, and reconfigurability of the manufacturing process (Bussmann & Sieverding, 2002). Each unit of HMS is represented by an autonomously working unit called holon (Gräßler & Pöhler, 2017). A holon, is defined in the holonic paradigm as a unit that advocates the use of autonomous and cooperative manufacturing units (Bussmann & Sieverding, 2002). These holons can interact and communicate with other holons and build a hierarchy, which in HMS is termed as holarchy (Gräßler & Pöhler, 2017).

If any assembly station breaks down, a multi-function (MF) station can be utilized to continue the process. These MF stations perform the same assembly operations as a set of stations on the main assembly line. The docking station (DS holon) decides whether (and when) to divert the part from the main line in case of a bottleneck and sends a signal to AGV (Autonomous Guided Vehicle) which transports the picked-up part. Hence, there is coordination between these holons. However, the assembly stations can still be manually operated. (Bussmann & Sieverding, 2002)

Reconfigurable Manufacturing System. Reconfigurable Manufacturing System (RMS) can be defined as an intermediate between DMS and FMS (Bi, Lang, Shen, & Wang, 2008). However, the concept of reconfigurability is applicable for a specific part family of products (Abou-El-Hossein et al., 2015) and customized flexibility (Koren & Shpitalni, 2010). It bridges the gap between the high flexibility and high cost of totally flexible machines and the low flexibility and low cost of fully dedicated machines. (Katz, 2007)(Abele, Liebeck, & Wörn, 2006) Reconfigurability at lower levels such as machines, cells, and shop floors are achieved by changing the hardware resources (Bi et al., 2008). The throughput of RMS is higher than the FMS throughput, but is lower than that of DMS for the same investment cost (Koren, Gu, & Guo, 2018). There are 6 core characteristics and principles that an RMS system can achieve: scalability, convertibility, diagnosability, customization, modularity, and integrability (Koren et al., 2018).

Reconfiguration technologies can be implemented on various aspects of an assembly station such as machine, inspection, system, (Koren et al., 2018) and small assembly stations. This system can also be called as a hybrid system where one can obtain volume flexibility with low investment shown in (Wiendahl et al., 2007). For instance, the incoming part can be fixed at a specified position on the turntable by the worker. As the turntable rotates, say 180 degree, a robot arm performs the fixed, repetitive operation (example - press). At the simultaneous time, the worker can place a new incoming part on the table. The system is economical because the movements are reduced to minimum (Wiendahl et al., 2007). Also, the output can be increased as the time required by the worker decreases.

Cognitive Aspects – HMI (Human Machine Interface). Being cognitive is about flexibility and faster adaption to change. The easy interaction between humans and machine is the key success of a cognitive factory. This is an alternative which reduces the complexity of a station or worker by actively supporting the worker with cognitive assistance systems. This also allows automatic knowledge transfer and collaboration between experts and unskilled workers (Gorecky, Worgan, & Meixner, 2011). Sensors and actuators form the main basis of the basic interaction between the assistance systems and humans (*Chang. Reconfigurable Manuf. Syst.*, 2008). As described in (Gorecky et al., 2011), this sensor network can be based on initial measurement units (IMU), cameras, and a processing units. To simplify the understanding, chosen two functional cases that can be derived:

a) Input/observation techniques

- Hand gesture recognition – the movement of hands (such as grasping) can be tracked by the sensors or a camera (Wallhoff et al., 2007) and this can be integrated with pick-to-light system.
- Pick-to-light system – to help the operator when the system has high product and component variety (Fasth-Berglund & Stahre, 2013).

b) Output modalities

- HMD – Head Mounting Devices such as retina display or AR (Funk & Schmidt, 2015) are suitable.
- Visual screen (Wallhoff et al., 2007) – visual screen at a static position showing the next steps would help if there variety in axles to be assembled.
- Text-to-speech system (Wallhoff et al., 2007) – since the assembly process is noise free, implementing text to speech systems which can help the worker with the assembly can be a reliable option.

4. Research Direction

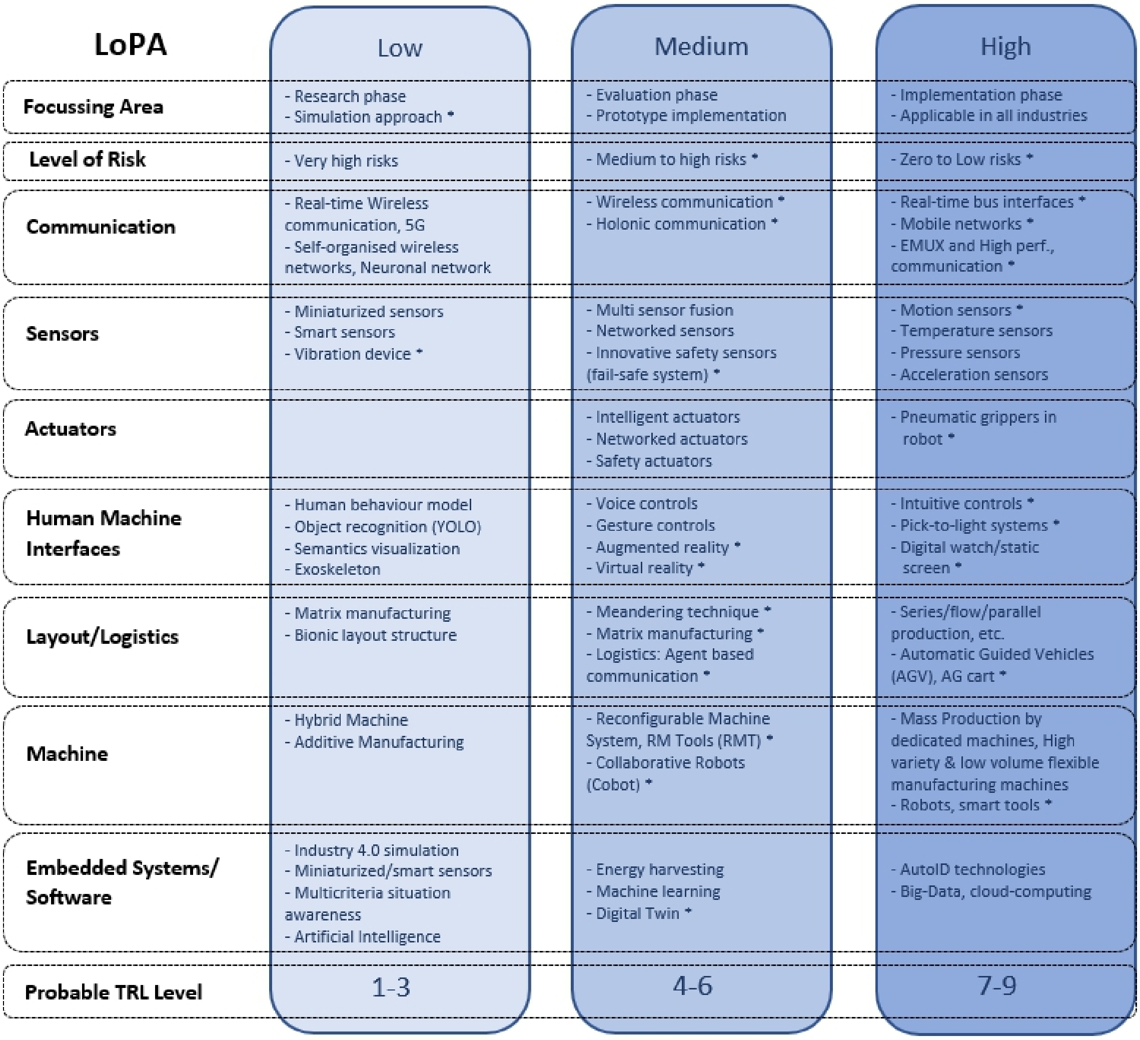
Achieving the right balance between the two opposed manufacturing systems by combining the different concepts explained above would be an ideal way of achieving the right flexibility. Each approach has that has been studied, would ideally fit the assembly line of low volume and high variety of batch production. Hence, an ideal direction is to implement the best aspects of each concept to achieve this flexibility, adaptability, and low costs. Table 2 summarises the benefits of each concept.

Table 2. Benefits of each concept.

Parameters	**Migration Manufacturing**	**Holonic Manufacturing System (HMS)**	**Reconfigurable Manufacturing System (RMS)**	**Cognitive Factory – HMI**
Ideal for	Increasing variants (Meichsner, 2008)	Flexible and dynamic allocation of resources (Gräßler & Pöhler, 2017)	Quick and easy adjustments to new products (Abou-El-Hossein et al., 2015)	Increasing productivity (Fasth-Berglund & Stahre, 2013)
Initial investment	10-30% less than FMS (Meichsner, 2008)	Higher than DMS, but lower than FMS	Lower than automated system (Wiendahl et al., 2007)	High initial equipment cost
Overall efforts for implementing	50-80% lesser compared to individual lines	Higher initial efforts than DMS	Depends on the level of reconfigurability	Comparatively lower than

	(Meichsner, 2008)			RMS and HMS
Other advantages	Faster break-even point than an additional line; 5-14% lesser variable cost (Meichsner, 2008)	Increase in productivity and throughput (Bussmann & Sieverding, 2002)	High responsiveness to fluctuating markets (Koren et al., 2018); movements of operator are reduced to minimum (Wiendahl et al., 2007)	Pick-to-light can be used for variety of tools (Fasth-Berglund & Stahre, 2013)

Achieving the maximum adaptability in the assembly process with a high variety of e-axles is the goal of these concepts as the current assembly process is designed for a single e-axle assembly. Also, maintaining the right balance between the automated systems and manual work keeping the small volumes, high variety and finally costs in mind. To enable this adaptability, as shown in **Figure 4**, the derived morphological matrix has various technologies based on their Level of Practical Application (LoPA). These technologies can also be classified individually on their Technology Readiness Level (TRL) (Böckenkamp, Mertens, Prasse, Stenzel, & Weichert, 2016). This matrix can be served as a building frame for adaptability. The aspects or features tagged with an asterisk (*) are the aspects that are being focussed on for the current assembly type and these aspects have higher practical implications.



LoPA	Low	Medium	High
Focussing Area	- Research phase - Simulation approach *	- Evaluation phase - Prototype implementation	- Implementation phase - Applicable in all industries
Level of Risk	- Very high risks	- Medium to high risks *	- Zero to Low risks *
Communication	- Real-time Wireless communication, 5G - Self-organised wireless networks, Neuronal network	- Wireless communication * - Holonic communication *	- Real-time bus interfaces * - Mobile networks * - EMUX and High perf., communication *
Sensors	- Miniaturized sensors - Smart sensors - Vibration device *	- Multi sensor fusion - Networked sensors - Innovative safety sensors (fail-safe system) *	- Motion sensors * - Temperature sensors - Pressure sensors - Acceleration sensors
Actuators		- Intelligent actuators - Networked actuators - Safety actuators	- Pneumatic grippers in robot *
Human Machine Interfaces	- Human behaviour model - Object recognition (YOLO) - Semantics visualization - Exoskeleton	- Voice controls - Gesture controls - Augmented reality * - Virtual reality *	- Intuitive controls * - Pick-to-light systems * - Digital watch/static screen *
Layout/Logistics	- Matrix manufacturing - Bionic layout structure	- Meandering technique * - Matrix manufacturing * - Logistics: Agent based communication *	- Series/flow/parallel production, etc. - Automatic Guided Vehicles (AGV), AG cart *
Machine	- Hybrid Machine - Additive Manufacturing	- Reconfigurable Machine System, RM Tools (RMT) * - Collaborative Robots (Cobot) *	- Mass Production by dedicated machines, High variety & low volume flexible manufacturing machines - Robots, smart tools *
Embedded Systems/ Software	- Industry 4.0 simulation - Miniaturized/smart sensors - Multicriteria situation awareness - Artificial Intelligence	- Energy harvesting - Machine learning - Digital Twin *	- AutoID technologies - Big-Data, cloud-computing
Probable TRL Level	1-3	4-6	7-9

Fig. 4. LoPA morphological matrix

5. Expected Results

The various technologies specified previously are to be implemented and verified with the help of verification models. To help implementing and testing the reliability of the adaptive systems, the recent approaches such as digital twin (Zhuang, Liu, & Xiong, 2018), plant simulation (Kikolski, 2016), DYNAMO++ methodology, FMEA, cost-benefit which are explained further can be enforced. These technologies help us in implementing and verification of the mentioned adaptive concepts.

5.1 DYNAMO++ Methodology (LoA matrix approach)

To move towards cognitive automation strategy, the scientific approach is to perform a DYNAMO++ methodology which further classifies into 12 steps including LoA (Level of Automation) Matrix (Fasth-Berglund & Stahre, 2013). This methodology helps in increasing the Level of Automation (LoA) (Fasth-Berglund & Stahre, 2013). The initial steps have been completed and the current LoA for the above e-axle assembly has been determined as shown in the **Figure 3.** In the current assembly process, there are 92 tasks which are distributed in the matrix as shown. The implementation of the cognitive aspects must be followed which increases the LoA in the directions shown by the arrows. This improvement in LoA is measured to determine the increase in cognitive and physical automation.

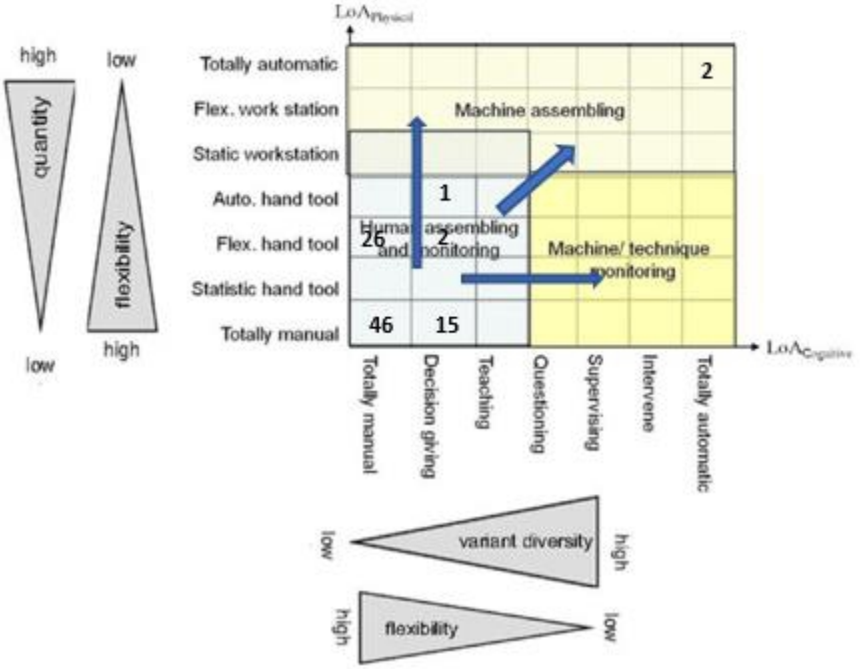


Fig. 3. LoA matrix (Dencker et al., 2009)(Lotter & Wiendahl, 2008)

5.2 Simulation Model

Currently, the assembly process is completely manual with high process times and this has been implemented in the assembly model in Plant Simulation tool. The simulation model helps in determining the bottleneck and the process clearly. A bottleneck is defined as a workstation limiting the production efficiency of the entire process (Betterton & Silver, 2012). The simulation model allows to calculate the effectiveness of various methods and processes (such as HMI, RMS, etc) and for a variety of e-axles. The creation of simulation model is done by using a seven-step approach as described by Law (Law, 2009). The computer simulation models can be freely improved and further simulations to the improved processes can also be applied freely (Kikolski, 2016).

The implementation was done as per the layout and station timings. The bottlenecks were clearly seen from the statistic graphs derived from the plant simulation. Furthermore, the changes (cognitive aspects) are also implemented in the simulation tool to determine the increase in throughput and efficiency of the system. Also, with the help of simulation tool, the errors during the ramp-up production are considerably reduced (Kikolski, 2016). Further, a simulation model can be used to visualize in real-time and focus on the affecting parameters (Kikolski, 2016). This approach can also be linked to the concept of digital twin (Zhuang et al., 2018).

5.3 Other Approaches

There are various other methodologies that are being done to determine the priority of each concept. Also, an FMEA analysis as done in (Pascu & Paraschiv, 2016), cost benefit analysis is done to improve the process performance. For example, a pair-wise comparison will be done for various cognitive features, an FMEA analysis depicting the benefits of each adaptive concept, and finally a cost-benefit analysis. The FMEA analysis illustrates the initial constraints and errors in a single e-axle, manual assembly. Thereafter, by implementing the adaptive technologies, these constraints are improved and the FMEA is again applied to justify it.

The described verification models would focus on improving the adaptability of the assembly process. It could also form a lead to the integration of reconfigurable assembly machines for high variety with human machine interfaces. Furthermore, by implementing these techniques, the costs of complex machines are relinquished. Thus, this would form as a basis for achieving a high variety production.

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