Kassem Ahmed, BSc.

Simulation Based Concepts for Adaptive Assembly Line for E-axles

MASTER'S THESIS

to achieve the university degree of

Diplom-Ingenieur

Master's Degree Program: Production Science and Management

Submitted to:

Graz University of Technology

Supervisor

Univ.-Prof. Dipl.-Ing. Dr.techn. Franz Haas

Institute of Production Engineering

Dipl.-Ing. Dr.techn. Markus Brillinger

Pro2Future GmbH

Graz, November 2019

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche gekennzeichnet habe.

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Graz, am…………………………………….	……………………………………….
(Datum/date)	(Unterschrift/signature)

Acknowledgement

I would like to express my appreciation to my thesis supervisors DI Dr.techn. Markus Brillinger and Univ.-Prof. DI Dr.techn. Franz Haas for their patience, assistance and continuous support. The door to Markus was always open whenever I needed guidance, had a question or required data, without his support this thesis would not have become real. I would like as well to thank Martin Bloder, BSc. for his ideas through the development of this project as well as his friendly support.

My gratitude goes to DI Muaaz Abdul Hadi who shared with me many ideas in this project as well as providing valuable suggestions regarding my thesis writing.

I would like to thank my mother for her extreme support during my masters and my family namely Dina, Omneya, Mostafa and May. Thanks for your patience, extreme love and motivating me during my whole work. Without you, I would not have been at this stage today.

Abstract

Global emissions phenomenon is considered a major challenge facing the globe nowadays. In order to limit the CO_2 emissions electro-mobility is strongly supported by the governments.

The different electric powertrains architectures used in today's electro-mobility were studied. One of the evolving architectures is the e-axles which offers weight reduction and lesser space requirements than other e-powertrain architectures.

This thesis is dealing with the development of high variety, low volume assembly line for e-axles. An assembly line with adaptive features was required in order to meet the thesis goal. The different configurations of the e-axles were studied to develop the product-process matrix. The U-shaped assembly line layout was applied and showed higher adaptive measures compared to other layouts studied. Different adaptive technologies and concepts were investigated, and technologies with high readiness level were selected.

Moreover, a simulation was conducted using Siemens Tecnomatix plant simulation software to evaluate the effects of the different technologies and layout on the throughput and rework percentages. As well, the sequence of products (e-axles) was simulated to evaluate the effect of sequence on the throughput of the assembly line.

The e-axle price was a main concern for this thesis as studies show that the price is a main factor affecting the sales of electric vehicles. The total cost of ownership model was created, and the labour, material, machines and development cost were calculated. Moreover, overheads and profit margins were calculated which resulted in e-axle price calculation.

In contrast to non-adaptive assembly line, the results show a high saving potential for the high product variety assembly of e-axle.

Kurzfassung

Das globale Emissionsphänomen gilt heute als eine der größten Herausforderungen für die Welt. Um die CO_2-Emissionen zu begrenzen, wird die Elektromobilität von den Regierungen stark unterstützt.

Die verschiedenen Architekturen der elektrischen Antriebsstränge, die in der heutigen Elektromobilität verwendet werden, wurden untersucht. Eine der sich entwickelnden Architekturen ist die E-Achse, die Gewichtsreduktion und geringeren Platzbedarf bietet als andere Architekturen.

Diese Arbeit beschäftigt sich mit der Entwicklung einer variantenreichen Fließbandanlage für E-Achsen. Um das Ziel der Diplomarbeit zu erreichen, war eine Montagelinie mit adaptiven Merkmalen erforderlich. Die verschiedenen Konfigurationen der E-Achsen wurden untersucht, um die Produkt-Prozess-Matrix zu entwickeln. Es wird das U-förmige Fließbandlayout verwendet, das im Vergleich zu anderen untersuchten Layouts höhere Anpassungsmaßnahmen aufweist. Verschiedene adaptive Technologien und Konzepte wurden untersucht und Technologien mit hoher Einsatzbereitschaft ausgewählt.

Darüber hinaus wurde die Simulation mit der Siemens Tecnomatix Anlagensimulationssoftware durchgeführt, um den Einfluss der verschiedenen Technologien und Layouts auf den Durchsatz und die Nacharbeitsquote zu bewerten. Außerdem wurde die Reihenfolge der Produkte (E-Achsen) simuliert, um die Auswirkungen der Reihenfolge auf den Durchsatz der Montagelinie zu bewerten.

Der Preis der E-Achse war ein Hauptanliegen für diese Arbeit, da Studien zeigten, dass der Preis ein Hauptfaktor ist, der den Verkauf von Elektrofahrzeugen beeinflusst. Das Total Cost of Ownership Modell wurde erstellt und die Arbeits-, Material-, Maschinen- und Entwicklungskosten berechnet. Außerdem wurden Gemeinkosten und Gewinnmargen berechnet, was zu einer E-Achsen-Preisberechnung führte.

Im Gegensatz zur nicht adaptiven Montagelinie zeigten die Ergebnisse ein hohes Einsparpotenzial für die Montage der E-Achse mit hoher Produktvielfalt.

List of Abbreviations

- Electric machine (EM)
- Electric vehicles (EV)
- Battery electric vehicle (BEV)
- European Union (EU-28)
- Alternative Fuels Infrastructure Directive (AFID)
- Total cost of ownership (TCO)
- Internal combustion engine (ICE)
- Internal combustion engine vehicle (ICEV)
- Plug in hybrid electric vehicle (PHEV)
- Pure electric vehicle (PEV)
- Austrian competence centres funding program (COMET)
- Deep groove ball bearing (DGBB)
- Level of practical application (LoPA)
- Technology readiness level (TRL)
- Pick to light (PTL)
- Pick to voice (PTV)
- Warehouse execution system (WES)
- Automated guided vehicle (AGV)
- End of line (EOL)

Table of Contents

1. Introduction 1
  1.1. Challenges facing electro-mobility 1
  1.2. Trends in e-powertrain 4
  1.3. Goal 7
    1.3.1. Research Aim 8
2. State of Art 9
  2.1. E-axles variants 9
    2.1.1. Transmission 9
    2.1.2. Differential 13
    2.1.3. Shifting mechanism 13
    2.1.4. Cooling features: 14
    2.1.5. Parking lock 17
    2.1.6. Sealing solutions: 17
  2.2. Adaptive technologies 19
    2.2.1. Pick to light system 20
    2.2.2. Pick to voice system 20
    2.2.3. Static screen 21
    2.2.4. Automated Guided Vehicle (AGV) 21
    2.2.5. Robots 23
  2.3. Layouts 24
  2.4. Simulation 26
  2.5. Cost 30
3. Concept 32
  3.1. E-axles configuration 32
    3.1.1. Expert interview 32
    3.1.2. Product process Matrix 33
  3.2. Layout 36
    3.2.1. Machines and Tools 36
    3.2.2. Categorizing 37
    3.2.3. Layout Design 38
  3.3. Productivity and Rework Analysis 40
    3.3.1. Failure modes 40
    3.3.2. Rating 42

3.3.3. Transfer to Percentage 42
3.3.4. Adaptive technologies 43
4. Tecnomatix Simulation 46
4.1. Basic Model 46
4.1.1. Simulation model 49
4.1.2. Simulation Results 54
4.2. Layout Model 54
4.3. Optimized layout 57
4.4. Adaptive Technologies 60
4.5. E-axles Sequence 61
5. Axle Cost 63
5.1. Material Cost 64
5.2. Labour cost 65
5.3. Machine costs 66
5.4. Development Cost 67
5.5. Overheads and profit margin 68
5.6. Results 68
Conclusion 72
List of Tables 73
List of Figures 74
Appendix 76
References 109

1. Introduction

The greenhouse effect is a major challenge facing the globe currently. The effects of greenhouse gases need to be limited, so the world leaders achieved Paris climate agreement within the framework of United Nations. The aim of Paris agreement is to limit the increase in the global average temperature to be below 2°C. Transportation is considered as a main contributor to the CO_2 emissions with 20% of the total emissions in the EU-28. 72% out of transportation sector contribution is coming from road transport. Electro-mobility is considered the enabler to limit the CO_2 emissions in the transportation sector. [1]

1.1. Challenges facing electro-mobility

The market penetration of electric vehicles (EVs) is going on slower pace than expectations. The European Union market as the focus of this thesis was studied, and the current market share of EVs is shown below in figure 1.

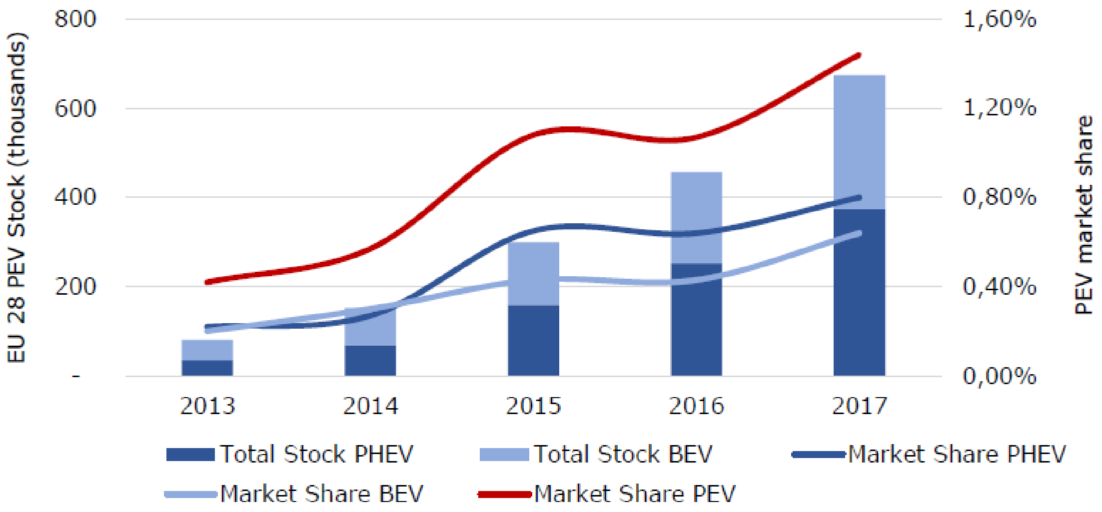


Figure 1: EV sales. Source: Policies (2018).

Figure 1 shows that the total market share within the EU-28 is below 1.6%. Many studies were conducted to investigate the slow market penetration of EVs. One of those studies is a study investigating the barriers for the adoption of EVs in EU-28 as shown below. [2]

---

[1] Hosseinpour and Chen (2015), NRDC (2017), Agency[Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11

[2] Cecere, Corrocher, *et al.* (2018) pp. 19–32

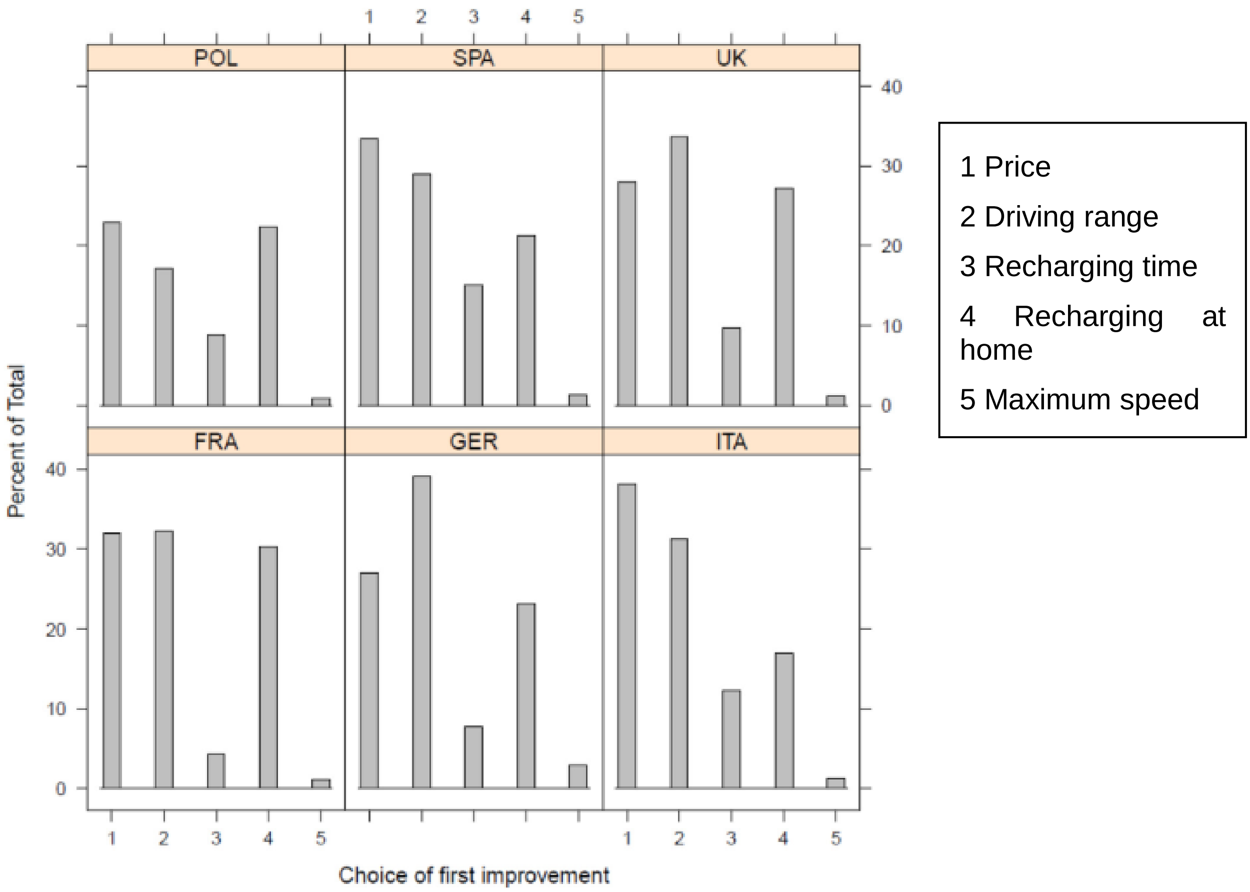


Figure 2: Barriers of electric vehicle. Source: Cecere (2018).

The study shows that the barriers are changing based on the country, in Germany the main barrier is the driving range while in Spain and Italy the main barrier is the price. As resulted from the study, the main barriers for the EVs widespread are:

- Price
- Driving range
- Charging time

Price

Study was conducted investigating the total cost of ownership (TCO) for EVs over 10 years' period. It showed that the TCO of EVs is lower than the internal combustion engines vehicles (ICEVs), but this is not conceived by the customers. The main determining parameter for the customers is the initial purchasing price of EVs. Based on this study initial price reduction is important factor affecting electric vehicles diffusion. [3]

Charging time and Stations:

Another trigger affecting the spreading of EVs is the charging time and the number of charging stations as well as the distribution of them. There are multiple charging modes and types affecting the charging timing shown below in table 1. [4]

[3] Weldon, Morrissey, *et al.* (2018) pp. 578–591
[4] Policies (2018)

Table 1: Charging modes. Source: Policies (2018)

Charging Mode	Description	Power	Kilometre per 10 minutes charging	Cost
Mode 1	Slow AC charging using home plugs, power up to 11 kW	Normal power charging	1-2	<800 €
Mode 2	Slow AC charging with semi active connection to vehicle, power up to 22 kW	Normal power charging	2-3	<2000 €
Mode 3	AC charging with active connection between charger and vehicle, power up to 43.4 kW	High power charging	21	1000-4000 €
Mode 4	DC fast charging with active connection between charger and vehicle, power up to 170 kW	High power charging	64	20,000 €

As mentioned in table 1, there are four different charging modes but those can be referred to two main categories:

- Normal power charging: which is charging with power <= 22 kW
- High power charging: which is charging with power >22 kW

Based on the suggestion from Alternative Fuels Infrastructure Directive (AFID) to have a maximum ratio of 10 EVs per charging point within the EU-28. The current market share shows that the most of the EU-28 are below such a ratio but considering Norway which is a market lead in EVs that ratio was not achieved. [5]

A case from Norway shows that the capital has a problem to supply EVs with charging points. Moreover, Oslo has 80,000 EVs and 1,300 charging points, which make the ratio up to 61. With such a ratio, the Norwegian Electric Vehicle association advised not to buy an EV unless the owner has a charging possibility at home or work. [6]

[5] Policies (2018)
[6] Policies (2018)

Only considering the current ratio of EV to charging points is not sufficient to judge the conformity of the current infrastructure for EV diffusion. Charging points per million inhabitants need to be studied. The charging points per million inhabitants is too low as shown below in figure 3.

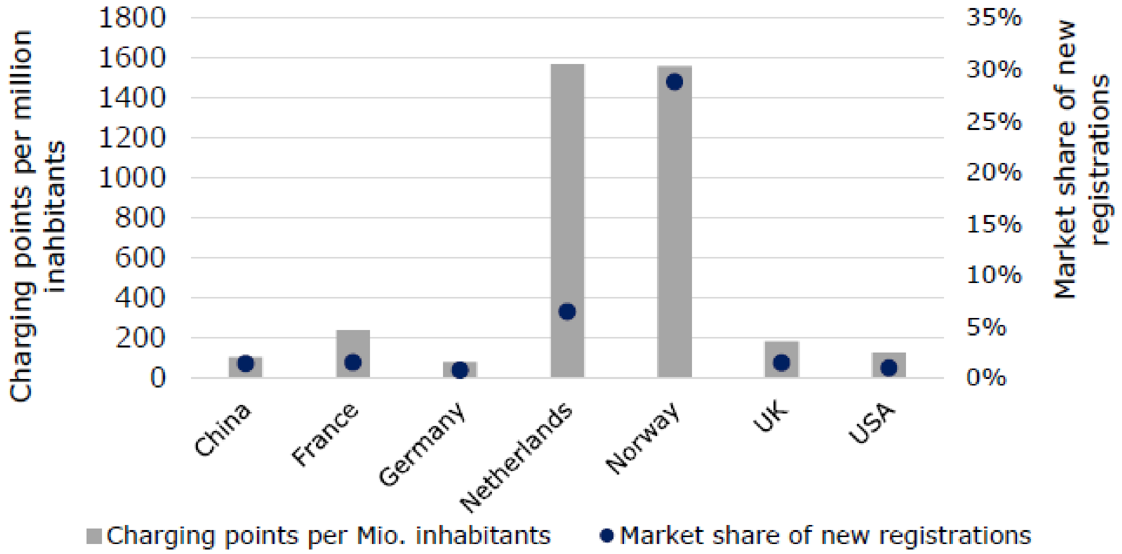


Figure 3: charging point density. Source: policies (2018)

Electrical distribution grid

The planning of the electricity grid is a long-term planning as the planning horizons for the power grids are decades. With the increasing number of EVs, the impact of EVs charging on the electricity grid needs to be studied. A study was conducted on the Swiss electricity grid for different market penetration of EVs and the impact of this penetration on the stability of the grid. The study showed that the Swiss electricity grid can be stable up to 16% market penetration of EVs (700,000 EVs) till 2040. Above the 16% penetration level, the probability of peak loads is getting higher. [7]

1.2. Trends in e-powertrain

In the last decade, many development efforts were performed on the e-powertrain due to the fact of its high efficiency (95%), and zero carbon emissions compared to the conventional powertrain, which has nearly 30% efficiency. [8]

These efforts resulted in different configurations and types of electrified powertrains; those can be summarized into four categories:

- Hybrid powertrain
- Power split powertrain
- Plug-in Hybrid powertrain
- Pure electric powertrain

[7] Florian Salah and others, 'Impact of Electric Vehicles on Distribution Substations: A Swiss CaseStudy'(2015)137 Applied Energy 88 <http://dx.doi.org/10.1016/j.apenergy.2014.09.091>.
[8] Chau and Li (2014) pp. 46–71

Hybrid powertrains are composed of electric machine (EM) and internal combustion engine (ICE). The mode of operation split the hybrid powertrains into:

- Parallel Hybrid
- Series Hybrid

The parallel hybrid operation mode is that both the EM and ICE are supplying the vehicle with power in parallel. Based on the position of the EM to ICE and transmission different parallel hybrid configurations occur, which affects the performance as shown in figure 4 below. [9]

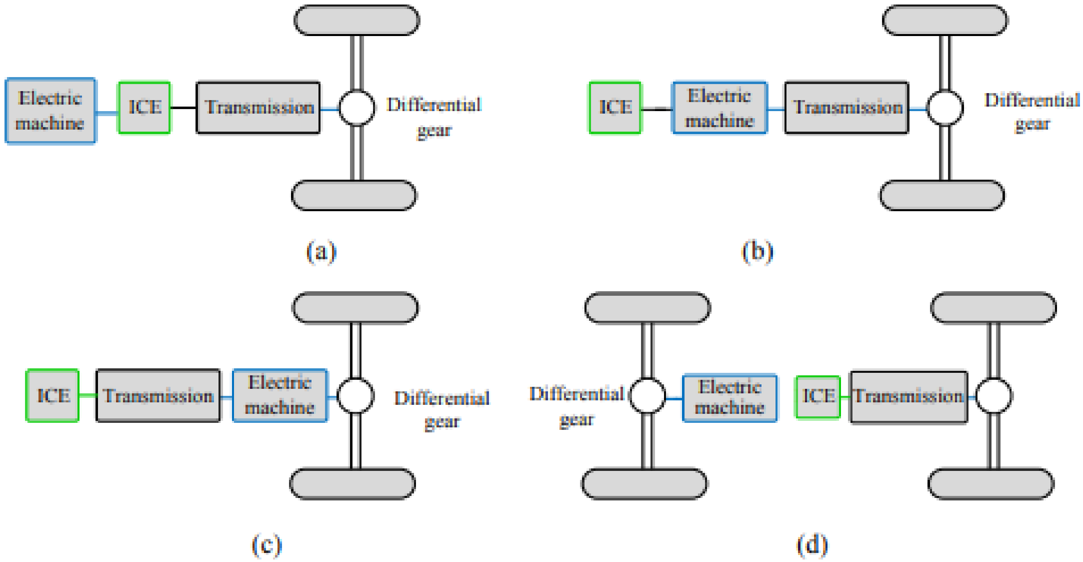


Figure 4: Parallel Hybrid powertrain. Source: Yang et al. (2016).

In figure 4 (a) the electric machine is acting as a starter for the ICE and called P1 configuration. In figure 4 (b), the electric machine and ICE both are adding power to the transmission and the vehicle can be driven in pure electric mode when ICE is shut off and called P2 configuration. In figure 4 (c), the transmission is located before the electric machine and called P3 configuration, but this configuration allows for same performance as P2 configuration. In figure 4 (d), the electric machine is positioned on a different e-axle than ICE. This configuration allows for independent operation of EM, and all-wheel drive configuration is achievable in P4 configuration. [10]

The series hybrid powertrain is a configuration where the ICE is working as a generator for the EM, which allows the ICE to work in the efficient region as shown in figure 5 below. [11]

---

[9] Yang, Ali, *et al.* (2016)
[10] Yang, *et al.* (2016)
[11] Borthakur and Subramanian (2019)

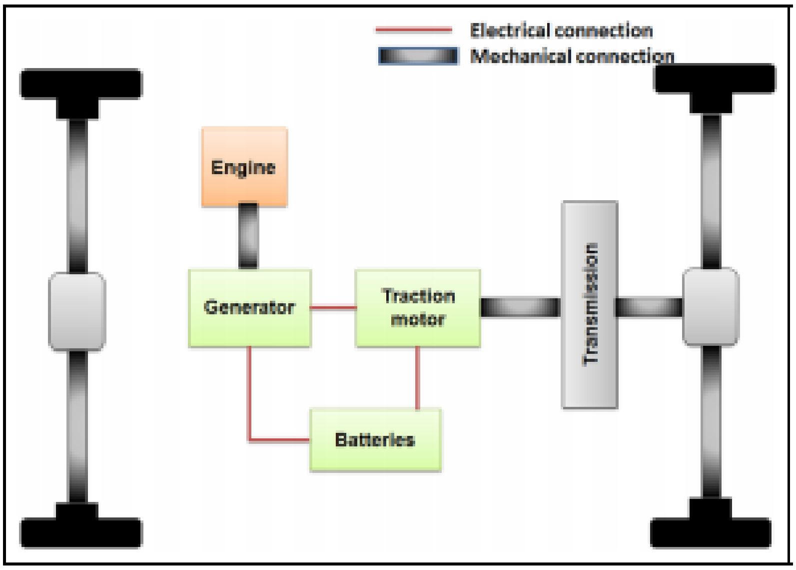


Figure 5: Series Hybrid Powertrain. Source: Borthakur (2019).

Power split powertrain a power split device is used typically planetary gear set, and the ICE power is split to two different paths; Electric path and Mechanical path. The ratio of electrical path to mechanical path is defining the driving mode of the vehicle. [12]

Plug-in Hybrid powertrain (PHEV) is composed of EM and ICE as in the hybrid powertrain but the difference is the charging method. The PHEV has a battery with large capacity which is able to be charged from the grid directly. [13]

Pure electric powertrain (PEV) is the simplest configuration of the e-powertrain. In this configuration, an electric motor along with a battery of high capacity is used to propel the vehicle with full electric power. The typical schematic for a PEV is shown below in figure 6.

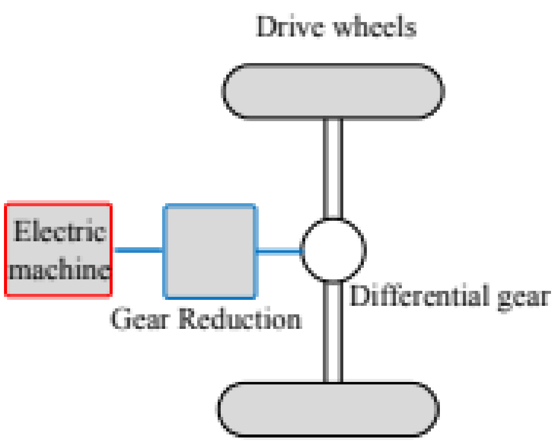
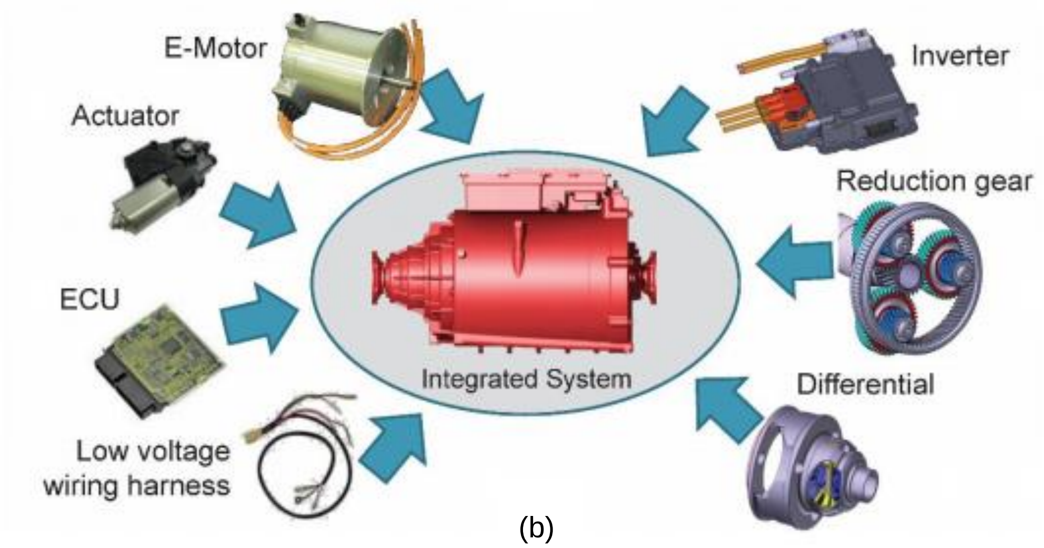


Figure 6: PEV schematic. Source: Yang et al. (2016).

[12] Yang, *et al.* (2016)
[13] Yang, *et al.* (2016)

The vehicle weight and space are strictly controlled parameters in the automotive industry. In order to reduce the e-powertrain weight and limit the space requirement, compact package is developed. The package integrates the differential, converter, transmission and motor together, and called e-axle as shown below in figure 7. [14]

(a)



(b)

Figure 7: Integrated e-axle (a) assembled view. Source: Nissan online source on 28.10.2019 (2019). (b) components view. Source: Schermann (2015).

1.3. Goal

The goal of this thesis is to develop assembly line for e-axles with high variety and low volume production capacity.

In collaboration with Pro2future GmbH, a leading company in powertrain development and TU Graz a project for development of a low volume adaptive assembly line for e-axles is initiated.

---

[14] Wu, Zhang, *et al.* (2015)

Pro2Future GmbH is a research centre located at TU Graz with a funding from the Austrian competence centres funding program (COMET). The company is related to studies of the "products and production systems of future". [15]

The project stakeholders are:

- **Pro2Future GmbH** manages the project, provides the means of project development and consultancy, and sets the project milestones (the data received by Pro2Future experts are referred to as expert interviews in this thesis)
- **TU Graz** represented by two master's thesis students working on the project along with Pro2Future GmbH
- **Partner Company** sets the requirements and provides the product data

The project started on the partner company side earlier, and initial layout is provided by the partner company for further development.

1.3.1. Research Aim

The research questions to be addressed through this thesis are:

- The adaptive concepts feasible to be used for a high variety, low volume production line
- The simulation of the adaptive concepts and their effect on the throughput
- The benefits of adaptive concepts implementation for low volume, high variety assembly lines

[15] Pro2Future[Online]. Available: http://www.pro2future.at/start-en/

2. State of Art

In this section, the different variants for e-axles will be discussed. The adaptive technologies which can be implemented for the layout is further studied. The assembly line layouts are studied in deeper details as well as simulation techniques. The cost methods for e-axles pricing and costing is further studied.

2.1. E-axles variants

The e-axles are studied according to different levels. Level one to state the different variants of the e-axles, level two the possible configurations of e-axles and level three the components which define the different configurations.

Thesis developed at Institute of Machine elements-TU Graz by Mr Rainer Hauptmann studied the different configurations for an e-axle. The study showed that for an e-axle the transmission, differential and speeds are the typical variants. After studying the outcome of the thesis with an expert, the cooling system is considered a fourth variant. Summarized variants and possible configurations are shown below in figure 8.[16]

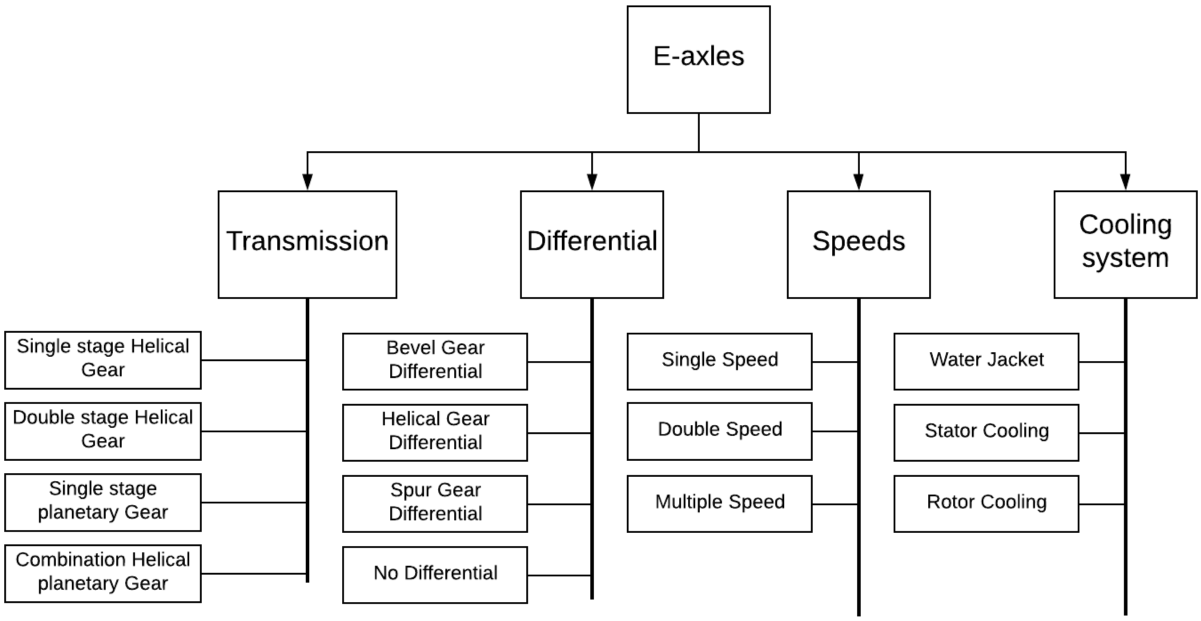


Figure 8: E-axles variants. Source: Own illustration.

2.1.1. Transmission

The transmission is used to convert the torque and speed from the power unit to the road. The basic components of a transmission are: [17]

- Shafts
- Gears
- Bearings

[16] Bloder (2019)
[17] Bertsche, Naunheimer, *et al.* (2013)

Shafts are a machine element which is responsible for power transmission. The shaft has a circular cross section and supports machine elements as Gears and Sprockets. The different types of shafts will not be studied in this thesis. [18]

Gears are the most common component for transmitting power between shafts as they allow for power transmission between shafts when they are: [19]

- Parallel
- Collinear
- Perpendicular and intersecting
- Perpendicular and nonintersecting
- Inclined at any arbitrary angle

As the shafts can be in different orientations, there are different types of Gears to address such orientations as shown in figure 9 below. [20]

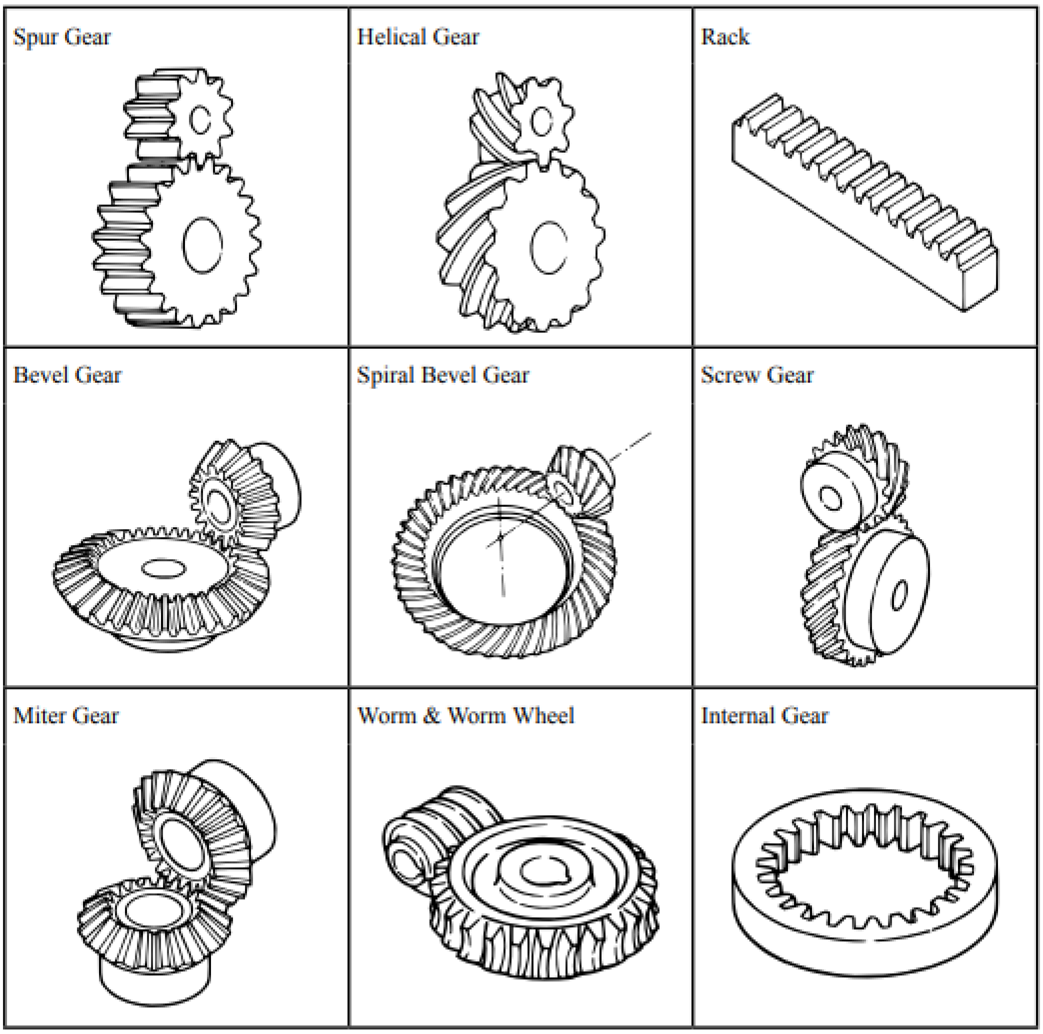


Figure 9: Gear types. Source: KHK Gear (2006).

[18] Bahandari (2016)
[19] Bahandari (2016)
[20] KHKGears,'IntroductiontoGearsFirstEdition'<https://www.khkgears.co.jp/kr/gear_technology/pdf/gear_guide_060817.pdf>.

For the sake of this thesis, only the gear types which were mentioned in the variants and configurations mentioned in figure 9 will be investigated further.

Spur gears are used when the shafts are parallel, and the teeth of the Gear itself is parallel to the shaft axis. The spur gear induces radial loads on the shaft. [21]

Helical gears are used for parallel axis shafts, but the teeth of the gear have helix on the pitch circle. The helix is defined by the helix angle. The Helical gears induce axial and radial loads on the shaft. [22]

Bevel gears are used to transmit power between two intersecting shafts. Bevel gears induce axial and radial loads on the shaft. [23]

Bearings are used in every mechanical equipment as there is a rotating part and a stationary part. This creates a need for a component to allow for the relative motion between both the stationary part (housing) and rotary/ movable part (shaft). The bearing allows for such motion with minimum friction, as well as sustain the loads of the relative motion. Bearings can be categorized based on the contact between the shaft and Housing into Sliding contact and rolling contact. [24]

For this thesis, only rolling contact bearings will be studied, based on the rolling element the rolling contact bearings are classified into ball bearings and roller bearings. Different types of rolling bearings are shown below in figure 10.

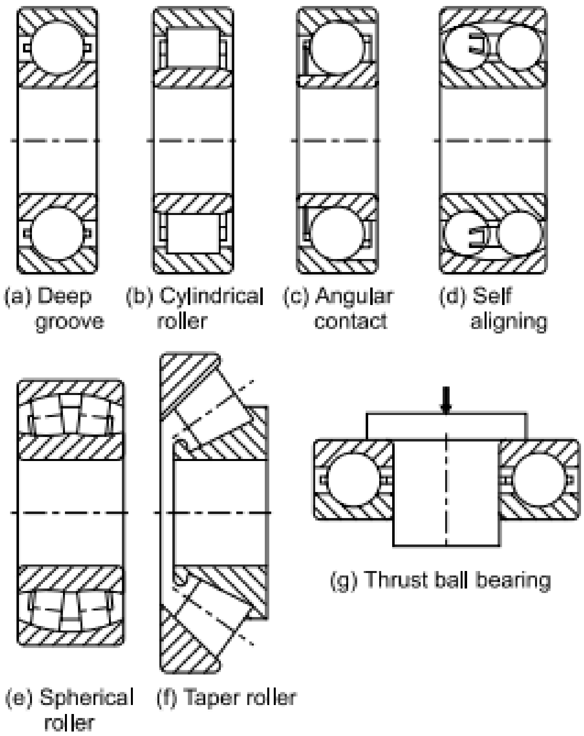


Figure 10: Different bearing types. Source: Bahandari (2016).

The most frequently used type of bearings in the transmission application are deep groove ball bearing and tapered roller bearings. Those two types will be further investigated.

---

[21] Gears (2006)
[22] Gears (2006)
[23] Gears (2006)
[24] Bahandari (2016)

Deep groove ball bearing (DGBB) is the most common type of bearings used in nearly all the applications. It is composed of balls, inner race and outer race. The radius of the ball is slightly less than the radius of curvature of the grooves, this allows for a point of contact between the ball and the races. [25]

Advantages of DGBB:

- It has a high load capacity
- It allows for both radial and axial Loads

Disadvantages of DGBB:

- It requires accurate alignment of shafts during design and assembly

The tapered roller bearing sustain loads both radially and axially, as It is composed of roller elements at an angle with the centre line of the bearing. The point of intersection between the centre line of the bearing and the rolling elements' axes is called apex point. The tapered roller bearing is composed of three parts; outer race which is called cup, rolling part which is called cage and the inner race which is called cone. [26]

Advantages of tapered roller bearing:

- It sustains very high radial and axial loads
- Allows for easy assembly and disassembly as the outer and inner race are separable

Disadvantages of tapered roller bearing:

- It requires axial preload

The positioning of the bearings on the shaft needs to be fixed during operation, and a preloading is required to have a higher lifetime. The positioning of the bearing is composed of radial locating and axial locating. The mostly used techniques for axial locating are: [27]

- Precision Lock nut
- Snap ring (internal or external)
- Sleeve
- Housing covers
- Spring washers

The most common techniques for the preloading of the bearings are (shown below in figure 11): [28]

- Fastening nut
- Springs and coils
- Interference fit between shaft / Housing with bearing
- Spacers

[25] Bahandari (2016)
[26] Bahandari (2016)
[27] HOUCKE
[28] NTN (2015)

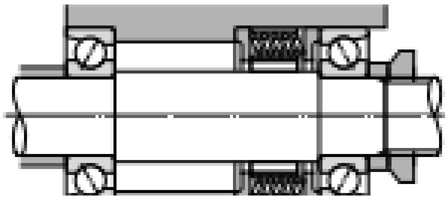


Figure 11: Extract preloading using spring. Source: NTN (2015).

2.1.2. Differential

The differential is considered as a sub-assembly provided by one of the differential suppliers, so the differentials configurations are not studied in this thesis.

2.1.3. Shifting mechanism

The typical shifting mechanism is composed of those main components Hub, blocking ring, sleeve and fork as shown below in figure 12. The fork is connected to the sleeve allowing for the sleeve linear movement over the hub to be connected to any of the blocking rings. The blocking ring is connected to both gear speeds. [29]

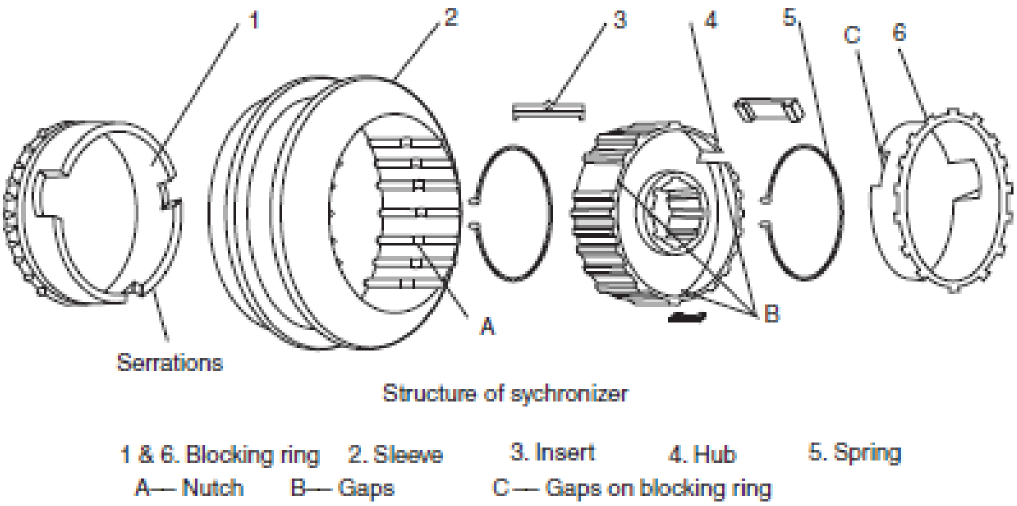


Figure 12: Shifting mechanism. Source: Zhang et al. (2018).

The fork can be triggered manually by the user or by the means of small electric motor and threaded shaft as shown below in figure 13.

[29] Zhang and Mi (2018)

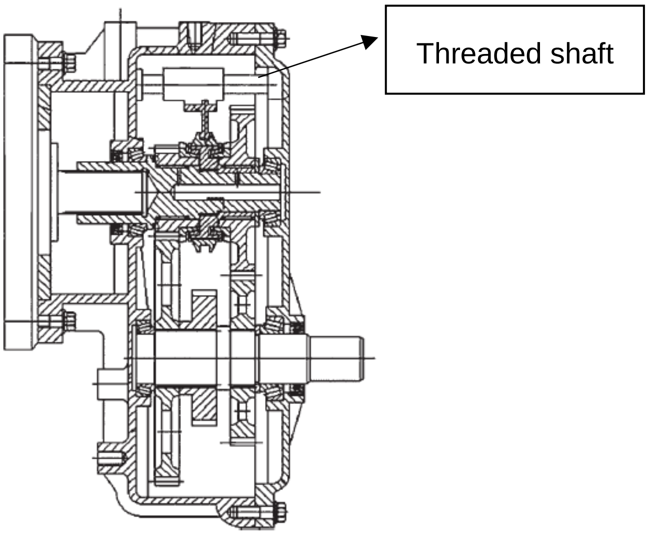


Figure 13: Shifting by electric motor modified. Source: Zhang et al. (2018).

2.1.4. Cooling features:

The Heat generated within electric motor is considered one of the challenges facing the operation of it in critical conditions as overload running, phase changing or asymmetric faults. The heat is generated due to electromagnetic efficiency and Mechanical power efficiency. [30]

This heat challenge requires heat dissipation solution within electric motors which can be summarized to three main solutions within the automotive industry. [31]

2.1.4.1. Natural passive cooling

The main idea of passive cooling is to dissipate heat with the surrounding using mainly the housing. The surface of the housing in order to allow for larger heat exchange needs to be optimized. Based on this, Fins are normally used on the outer surface for the Housing as shown below in figure 14.

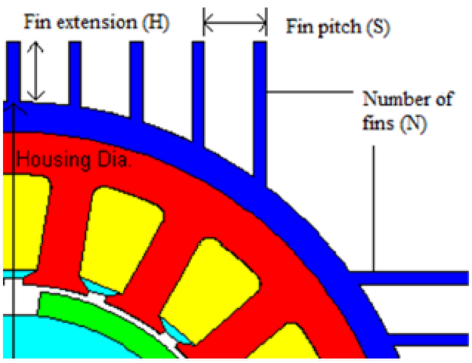


Figure 14: Natural passive cooling. Source: Gai et al. (2019).

[30] Gai, Kimiabeigi, *et al.* (2019)
[31] Gai, *et al.* (2019)

2.1.4.2. Forced air cooling

The main difference between forced cooling and the passive cooling is the use of external device. The forced cooling is using external device to create flow to exchange heat which results in higher power dense and compact motors.

The forced air cooling has two main types:

- **Enclosed fan cooling** as shown below in figure 15, this system is composed of two fans internal and external. The internal fan is mounted on the rotor shaft and responsible of creating internal flow to extract the heat from the motor and exchange it to the Housing. The external fan is responsible of creating flow over the housing and the flow acts as sink for the heat. [32]

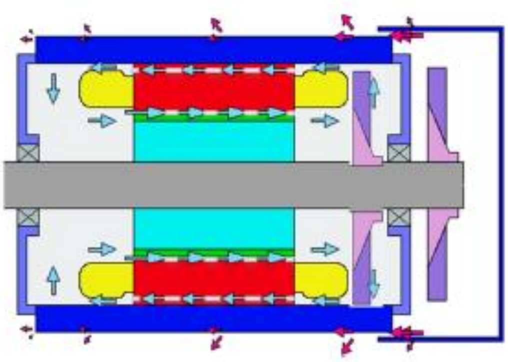


Figure 15: Enclosed fan cooling. Source: Gai, et al. (2019).

- **Open fan cooling** as shown below in figure 16, the open fan cooling is composed of single fan on the rotor shaft. Where the fan creates the flow to extract heat from the motor. The fan gets the air from the ambient environment. The main drawback of this system is that such a system needs to be disassembled frequently to be cleaned. [33]

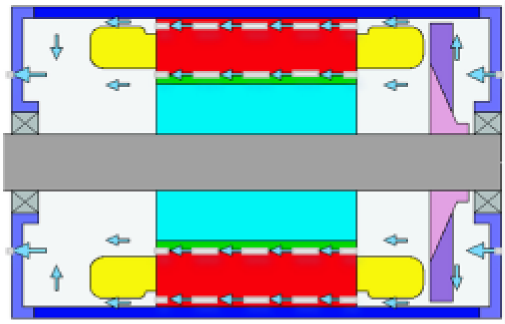


Figure 16: Open fan cooling. Source: Gai et al. (2019).

[32] Gai, *et al.* (2019)
[33] Gai, *et al.* (2019)

2.1.4.3. Forced liquid cooling

The forced liquid cooling is different from forced air-cooling by using of liquid normally water for the cooling of the electric motor. This system is normally used for high power electric motors. There are three main methods of forced liquid cooling which are:

- **Water Housing Jacket**: this method is widely used for cooling approaches where liquid is responsible of extracting heat generated in coils, stator and rotor. The main heat extraction method is conduction and the sink are the ambient environment via convection. The geometrical tolerances make a great difference in efficiency in this approach as shown below in figure 17.

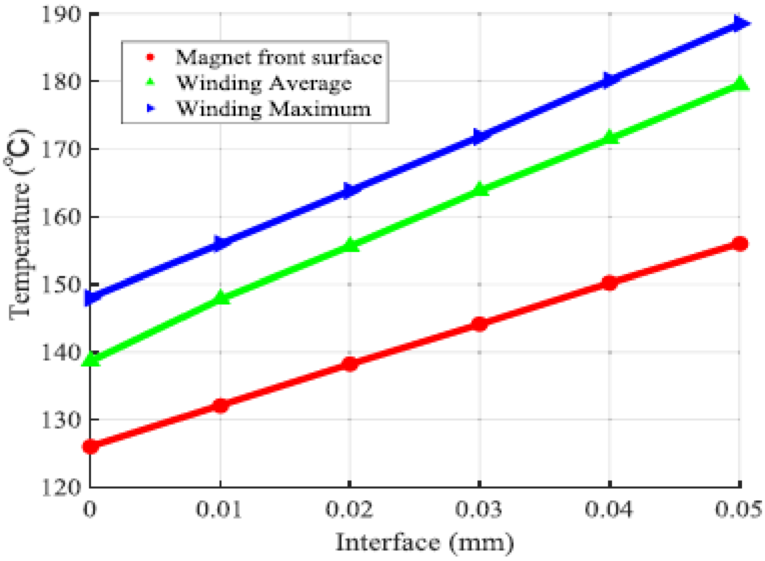


Figure 17: Housing jacket tolerance effect. Source: Gai et al. (2019).

- **Stator cooling system**: this method is using cooling slots in the stator laminations. Another method as well for stator cooling is the wet stator cooling. A liquid is to pass between the armature end windings and stator laminations where a sleeve is used to prevent the liquid from entering the air gap to the rotor as shown below in figure 18. [34]

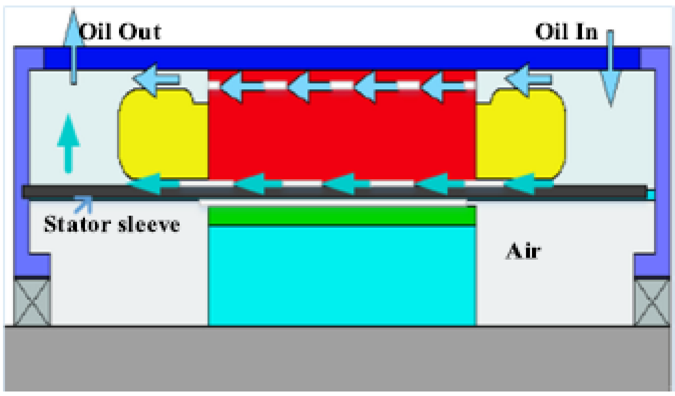


Figure 18: Stator cooling sleeve. Source: Gai et al. (2019).

[34] Gai, *et al.* (2019)

- **Rotor cooling method:** the main idea of this method is to use a hollow rotor with a hollow shaft. The hollow shaft contains the cooling tube which is coupled with the coolant as shown below in figure 19. [35]

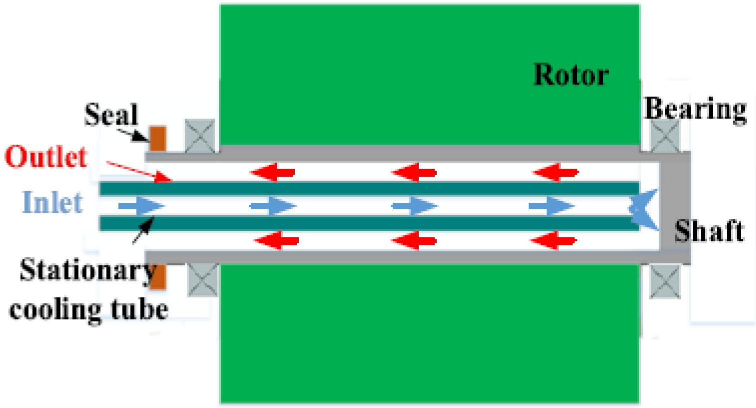


Figure 19: Rotor cooling method. Source: Gai et al. (2019).

2.1.5. Parking lock

The parking lock mechanism is used to prevent the rotational movement of the output shaft of the transmission. A typical parking lock mechanism is shown below in figure 20. Where the parking gear is connected to the output shaft, actuator rod which triggers the movement of the parking pawl. When the parking pawl is triggered, the parking pawl is connected to one of the outer teeth of the parking gear and lock the output shaft from rotation. [36]

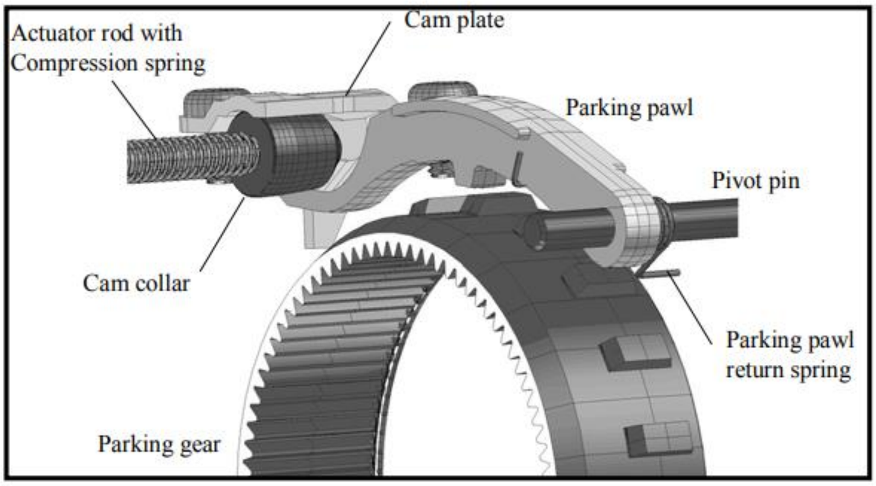


Figure 20: parking lock mechanism. Source: Mahale et al. (2007).

2.1.6. Sealing solutions:

Based on data received from an expert in Transmission field and working on the same project, there should be two main sealing points and third based on the cooling system which are:

[35] Gai, *et al.* (2019)
[36] Mahale, Patwardhan, *et al.* (2007)

- The motor output shaft sealing: the motor needs to be sealed against the oil located in the transmission. This sealing is high speed radial sealing as the motor output shaft is typically rotating at around 20000 rpm. [37]
- The differential/transmission output shaft: the driveshaft needs to be sealed against the ambient environment, this is typically a radial sealing with a plastic cover to save the sealing against dust and other environmental contaminants

- Rotor cooling shaft sealing: this sealing needs to seal the motor from the coolant

The radial sealing is typically made for shafts to keep lubricants, and to save the bearings. A typical radial sealing is shown in figure 21(b). [38]

The labyrinth is typically composed of two parts, the main function of labyrinth seal is to create a longer path for lubricants and contaminants to follow to enter/exit the system. As well, it uses the centrifugal force generated from shaft rotation to keep lubricants and contaminants. As shown below in figure 21(a). [39]

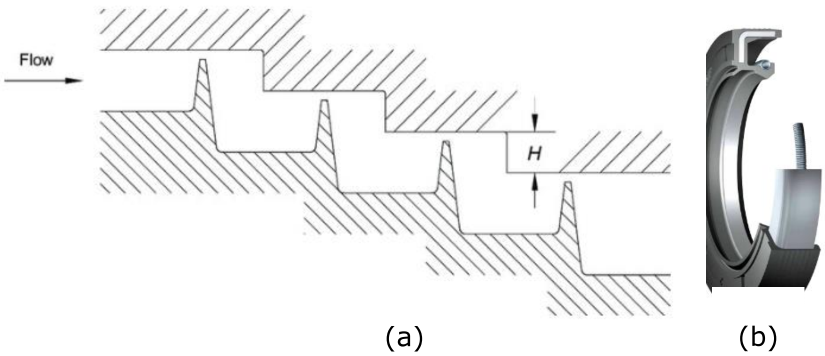


Figure 21: (a) Extract labyrinth configuration. Source: Khayal (2017), (b) radial shaft seal. Source: SKF (2014)

[37] Bloder (2019)
[38] SKF (2014)
[39] Khayal (2017)

2.2. Adaptive technologies

The high number of configurations require higher adaptive level of the assembly line. A study was performed for the assembly of e-axles with high product variety to define the different adaptive technologies to be implemented. The study classified the technologies based on level of practical application (LoPA) and technological readiness level (TRL). The result of the study is shown in figure 22. [40]

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

Figure 22: Adaptive technologies for e-axles. Source: Brillinger et al (2019).

The different technologies are categorized in the study based on the level of technology readiness level into low, medium and high. The different fields are studied and categorized into communication, sensors, actuators, human machine interfaces, layout and logistics, machine and embedded systems and software.

[40] Brillinger, Hadi, *et al.* (2019)

The human machine interfaces, layout and logistics and machine categories are of interest within this thesis and are further studied.

2.2.1. Pick to light system

Pick to light system is an assistive picking system where labels with sensors are placed on rails onto shelves in front of the parts' bins. The system is connected to the warehouse execution system (WES) where the picking steps are arranged. The label flashes for the part need to be picked in sequence as shown in the system architecture in figure 23. [41]

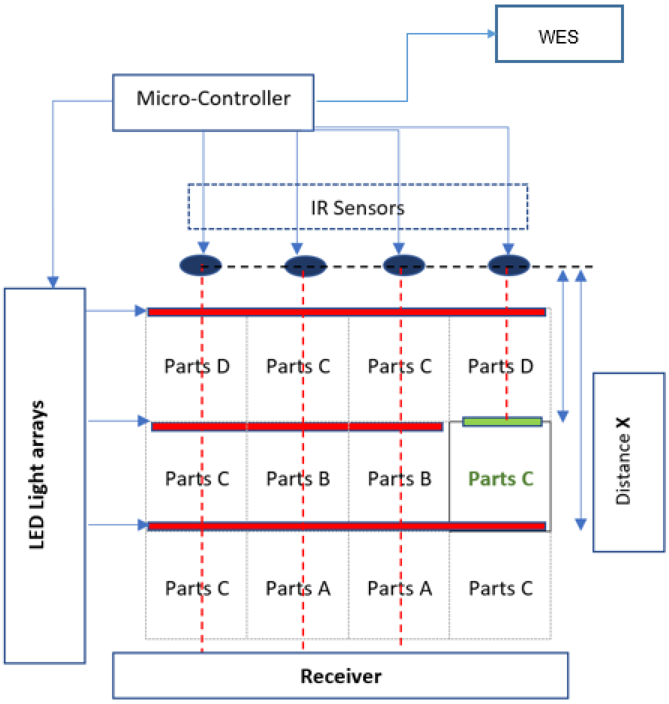


Figure 23: Modified pick to light architecture. Source: Abdul Hadi (2019)

2.2.2. Pick to voice system

The pick to voice technology is an assistive picking technology where the worker is using a headset. The picking steps and instructions are recorded, and the worker listens to steps according to the warehouse execution system as shown in the system architecture in figure 24. [42]

[41] Dukić, Česnik, *et al.* (2010)
[42] Dukić, *et al.* (2010)

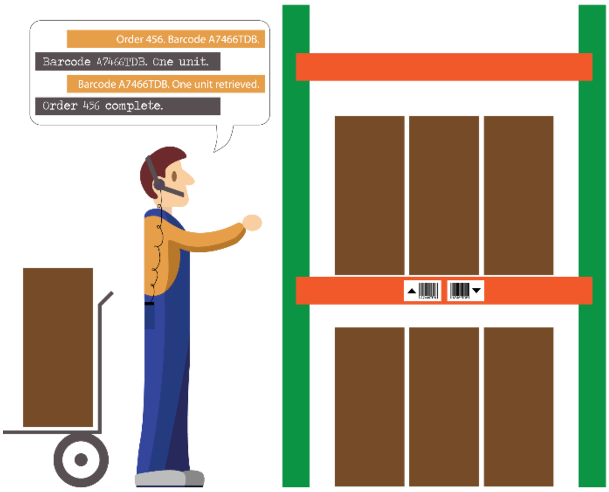


Figure 24: Pick to voice system. Source: rebstorage.com online source on 29.10.2019.

2.2.3. Static screen

The static screen technology as shown below in figure 25 is an instructions visualization technology which is used in the assembly steps instructions. Based on a study performed showed that the visualized instructions using pictures allow for a higher knowledge transfer than text or video instructions. [43]

Figure 25: Picture instructions on screen. Source: Belusko et al. (2016).

2.2.4. Automated Guided Vehicle (AGV)

One of the main challenges facing the flexible manufacturing systems is the handling of materials and goods. The automated guided vehicle is considered as an enabler for a flexible material handling between stations. [44]

AGVs are split to different types, the types of interest are:

- Forklift AGV
- Piggyback AGV
- Assembly AGV
- Mini AGV

[43] Beluško, Hegedüš, *et al.* (2016)
[44] Ullrich (2015)

Forklift AGV is used with loading and unloading pallets with a simple route between two specified locations or a complex route (multiple locations). It is also able to reach different heights as well as loading pallets from the ground level as shown in figure 26. [45]

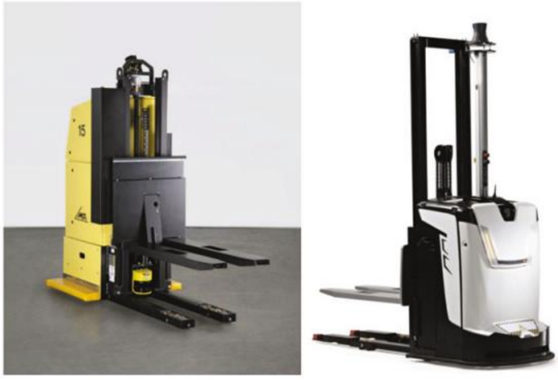


Figure 26: Forklift AGV. Source: Ullrich (2015).

Piggyback AGV is a lateral load handling AGV for pallets, cages and containers. The loading features make piggyback suitable for handling the materials directly from the assembly line with a typical height of 60 cm. The main disadvantage is that 60 cm height need to be maintained through the assembly line. Piggyback AGV is shown in figure 27(a). [46]

Assembly AGV is a special design AGV where the AGV holds a specific fixture, and the AGV moves through the different stations with the mounted parts on fixture. The assembly steps are performed directly on the fixture. Assembly AGV is shown in figure 27(b).

Figure 27: (a) Piggyback AGV (b) Assembly AGV. Source: Ullrich (2015).

Mini AGV is intelligent, flexible and small AGV which quickly performs tasks and pickups. The idea behind the mini AGV is that the parts come to the worker and not the worker who is seeking the parts. Many AGVs can be implemented because of its affordable price, and this allow for a high plant coverage. Mini AGV is shown in figure 28. [47]

[45] Ullrich (2015)
[46] Ullrich (2015)
[47] Ullrich (2015)

Figure 28: Mini AGV. Source: Ullrich (2015).

2.2.5. Robots

Industrial robots proved benefits in the assembly tasks specially tasks which are tedious and repetitive as the quality and efficiency increased. A case study was performed to assemble rear frame in aircraft engine where accuracy of assembly is critical, and a study performed by Ford for engine assembly. Two technologies where investigated for the assembly: [48]

Robot Force Control is a used technology in riveting and clamping of parts where the assembly force is controlled by a feedback control. This control method eliminates deformation or sliding effects. [49]

Robot Vision Control is a used technology where a camera is mounted on the robot, and the camera detects the object using high dynamic range imaging. Based on the image, the robot reorients its position and starts assembly as shown in figure 29. [50]

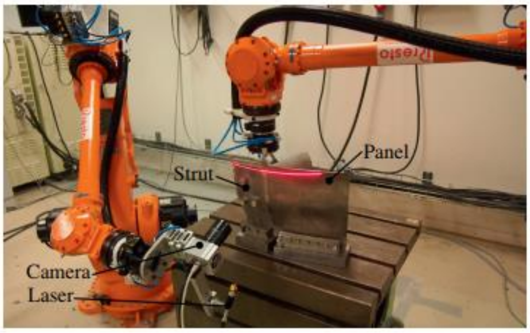


Figure 29: Robotic Vision control. Source: Tingelstand et al. (2014).

[48] Tingelstad and Egeland (2014), Gravel and Newman (2001)
[49] Tingelstad, *et al.* (2014), Gravel, *et al.* (2001)
[50] Tingelstad, *et al.* (2014), Gravel, *et al.* (2001)

2.3. Layouts

The layout planning is considered one of the main topics in industry dated back to the 1950s. Many studies showed that the material transportation accounts to nearly 20-50% of the manufacturing operating costs. This portion can be reduced up to 30% with proper layout planning. [51]

The different facility layouts were studied, and figure 30 below shows recommended layout to be used based on the product variety and production quantity.

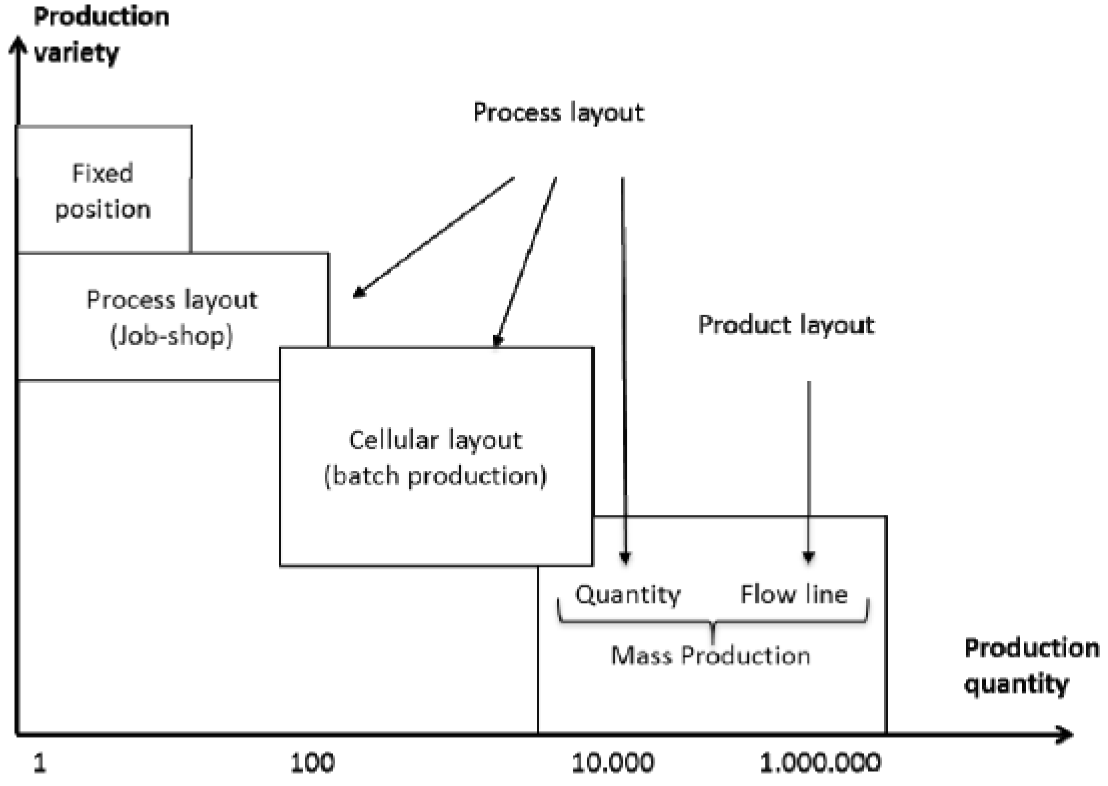


Figure 30: different layouts. Source: Carlo et al. (2013).

- Fixed position layout: it's the layout where the product is kept in place and manufacturing steps are performed on the product directly, this layout is typically used in the ship industry
- Process layout is the layout where the production is divided into shops and each shop is responsible for specific processes
- Cellular layout is the layout where the production facility is divided into cells each with a specific number of machines and labour. Each cell is producing specific number of products with specific variants
- Flow line layout is the layout where the production facility is composed of specific flow line and used for high volume production

When speaking about product variety, a new parameter needs to be considered which is the degree of similarity. The degree of similarity defines how different are the products from the

[51] De Carlo, Arleo, *et al.* (2013)

manufacturing steps. If the difference does not affect the process as size difference, then products are called to have a high degree of similarity. [52]

The difference between e-axle's configurations is in the shape or the sequence of parts to be assembled. The assembly process of the different e-axles' configurations can be considered with a high degree of similarity. For this reason, the flow line is analysed further.

Different flow line layout is studied as shown in figure 31 below for the typical arrangement of stations. [53]

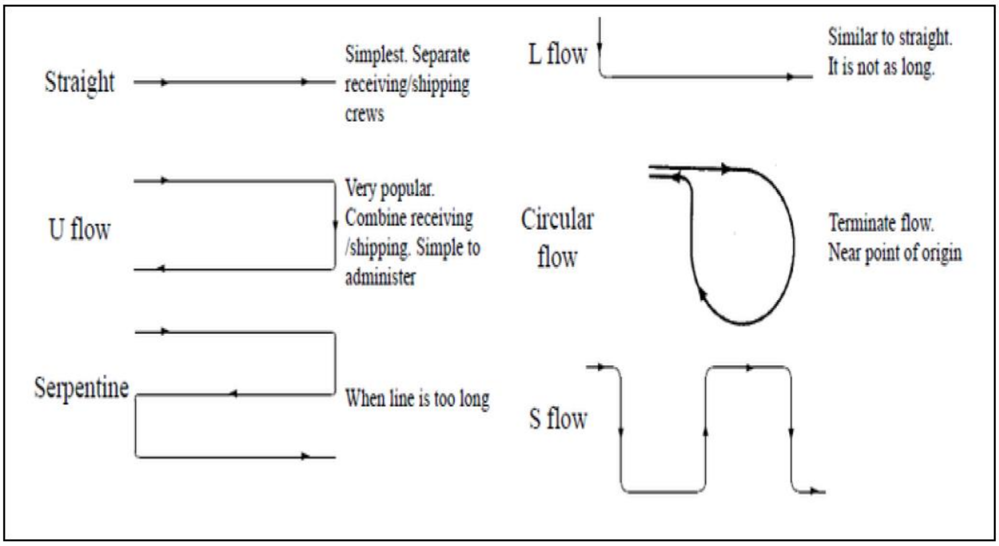


Figure 31: Flow lines. Source: Kassir (2015).

- The straight flow is the simplest flow line layout where the stations are arranged in straight line. This layout is feasible for mass production with very low product variety
- The L flow is the solution for the limited space when straight flow line is not applicable due to space limitation
- The S flow is used for very long flow lines and space is limited
- The U-shaped flow line is used for fluctuating demands and high product variety, as the workers no. can be reduced based on the demand, and the reallocation of workers based on the product to be produced is possible as shown below in figure 32. [54]

[52] De Carlo, *et al.* (2013)
[53] Kassir (2015)
[54] Ohno and Nakade (1997)

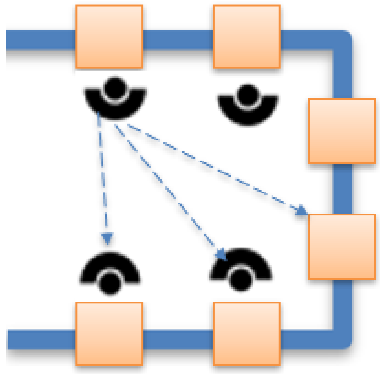


Figure 32: Workers in U-shaped assembly. Source: Own illustration.

2.4. Simulation

Simulations are typically used to cut the time to market by representing a physical process or layout as a model. Simulations are used for the evaluation, optimization and analysis of different real physical cases. [55]

There are different types of simulations and can be categorized based on three variants:

- Timing of change: the simulation is dependent or independent on time
- Randomness: the simulation runs always provide same/different result
- Data Organization: Grid based or mesh free

Figure 33 below shows the different types of simulations. [56]

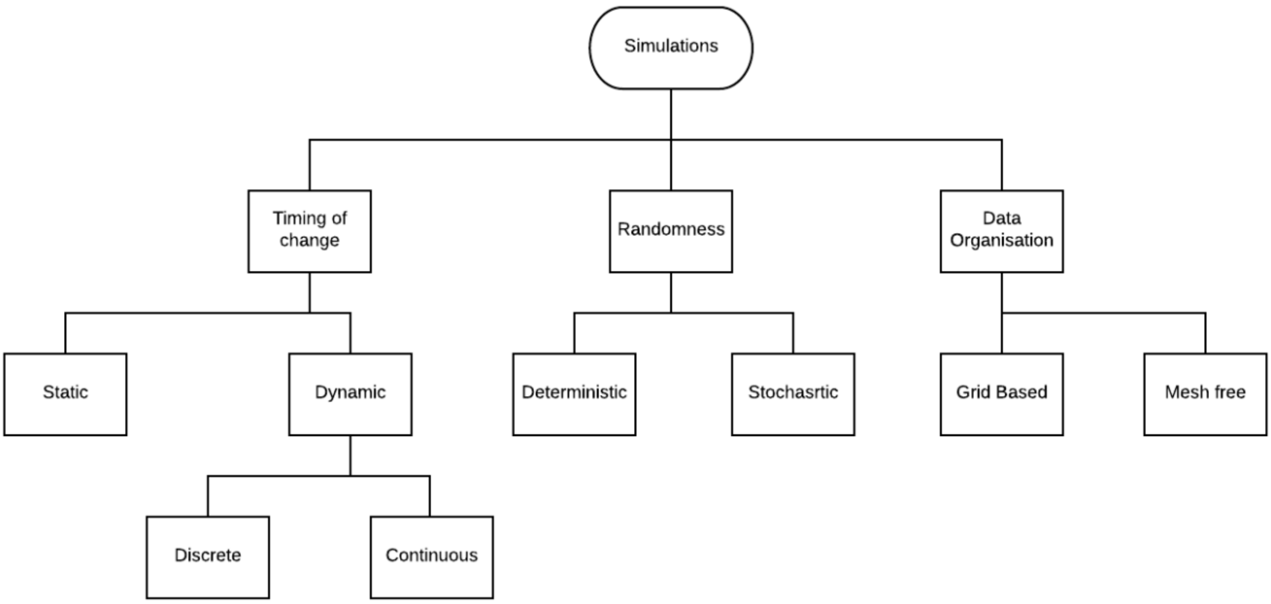


Figure 33: Simulation types. Source: Own illustration.

- Static simulation is the simulation type which is independent on time
- Dynamic simulation is the simulation type which dependent on time and either discrete where the time is represented as steps of events occur or continuous where events are continuous

[55] Heilala (1999)
[56] Mourtzis, Doukas, *et al.* (2014)

- Deterministic simulation is the simulation when run several times, its results is the same result
- Stochastic simulation is the simulation when run several times, it results is a different result
- Grid based simulation is the simulation where the data is stored in cells and updates of the data is based on the earlier statues
- Mesh free simulation is the simulation where the data "of individual particles and updates look at each pair of particles

The simulation type of concern is the discrete simulation where the changes are done at a specific point in time. The simulation as well need to provide the same results when repeatedly run, as this simulation is used for:

- Facility planning
- Optimization of current facilities
- Material Handling simulations
- Operational planning

The main discrete simulations for facility and plant simulations on the market: [57]

- Siemens Tecnomatix
- Enterprise dynamics
- Arena
- Show flow

One of the requirements of the partner company is to verify the concepts using Siemens Tecnomatix, so it is used throughout this thesis.

Siemens Tecnomatix allow for the following features: [58]

- Visualization of the model in 3D
- Detecting of bottlenecks
- Energy usage calculation
- Analysing layouts

When simulating a manufacturing system, the following parameters are of concern:

Table 2: Modified manufacturing system requirements. Source: Bangsow (2016).

Category	Parameter	Category	Parameter
Product	Product flow, routing and resources needed Bill of materials	Production control	Assignment of jobs Task selection of work centres Routing decisions
Labour	Shift schedules Job duties	Suppliers	Ordering Receipt and storage Delivery to work centres
Equipment	Rates and capacities	Storage	Suppliers

[57] Kikolski (2016)
[58] Bangsow (2016)

	Failures: time to failure, time to repair		Spare parts Work in process
Production schedules	Make to stock Make to order	Final goods	Packing and shipping Order consolidation Paperwork Loading trailers
Work centres	Processing Assembly Disassembly	Physical layout	Layout
Maintenance	PM Schedule Time and resource required Tooling and fixtures		

The simulation steps as described in the "seven steps approach for conducting a successful simulation" are shown below in figure 34. [59]

[59] Law (2008)

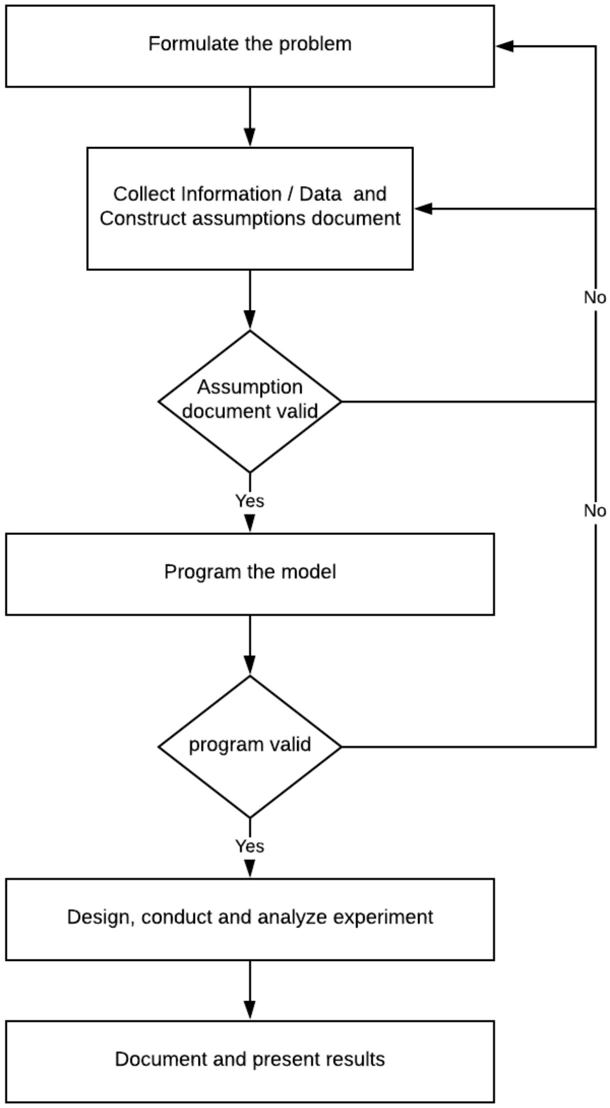


Figure 34: seven steps approach. Source: Law (2009).

- Step 1 shows the precise description of the simulation problem between the project stakeholders and communicate the expected result and time frame of the simulation
- Step 2 shows the data collection for the model parameters and document the list of assumptions made
- Step 3 is a decision step where the list of assumptions is evaluated regarding its validity
- Step 4 shows the programming of the model into the simulation language
- Step 5 shows the validation of the programmed model with an existing one, and if not, is the result obtained from the model is reasonable
- Step 6 shows the design and analysis of the model
- Step 7 shows the documentation of the whole simulation experience and the results with the assumptions made. [60]

[60] Law (2009) pp. 24–33

2.5. Cost

Cost of units is a major topic in manufacturing and service industry especially when it comes to selection of suppliers. As an effort to address this topic a new model was developed in United States of America 20 years ago which is Total Cost of ownership (TCO). TCO is defined as a model which does not only include the direct costs of goods but also the indirect costs, and not only the purchasing price of goods but also the lifecycle cost of goods. As shown in figure 36 below total cost of ownership is equal to the acquisition price and the sum of associated costs minus the salvage value. [61]

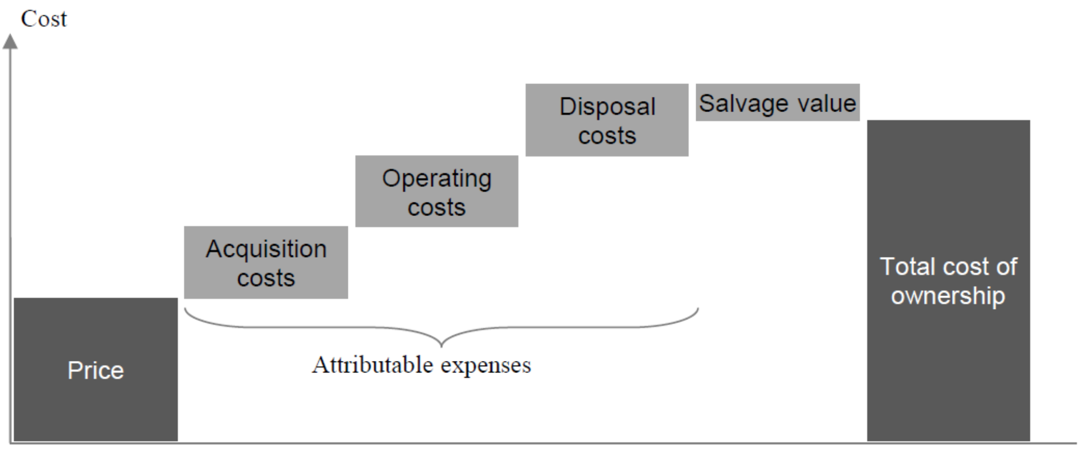


Figure 35 Total cost of ownership model. Source: Rosenback (2013)

From the TCO model, the following can be concluded:

- The additional costs in the model are dependent on the user/manufacturing facility (In-house costs)
- Acquisition cost is the costs of acquiring the product or the service i.e., shipping costs, insurance costs, storage cost
- Operating cost is the costs of usage the material/ product i.e., energy cost, downtime cost, Maintenance cost
- Disposal cost is the costs of disposing the material/ product i.e., recycling cost, selling costs
- Salvage value is the price of reselling the material/ good after end of life. [62]

The framework for implementing TCO is defined as shown in figure 36 below is composed of different steps:

1. There should be external or internal need to develop the TCO, the first step is to define those needs and drivers for TCO development
2. The objectives of the TCO development need to be defined, and the objective must meet the internal / external needs and drivers
3. Forming a team with a team leader for the TCO project proved benefits over the sole work of the purchasing team on the TCO. Cross functional team allows for different perspectives and ways of thinking

[61] Rosenback (2013)
[62] Parkhi (2015)

4. Till now no costs are calculated, at this step the costs are to be identified and to be categorized into different category as shown earlier in the TCO model
5. The data need to be evaluated at this stage and assumed costs need to be distinct from the calculated costs
6. Decision making is possible at this stage based on the results of the TCO

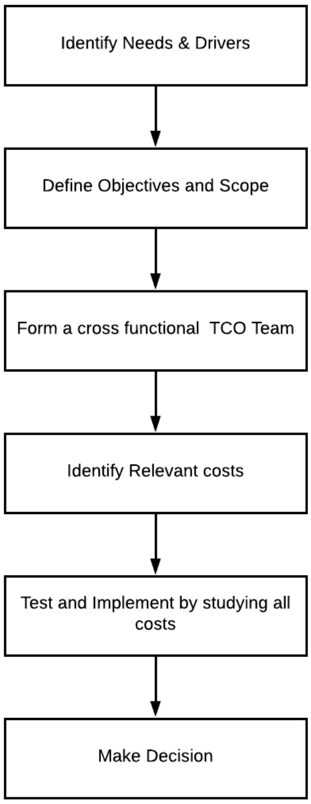


Figure 36: Modified TCO Framework. Source: Palkhi (2015).

3. Concept

In this section, the steps of developing the assembly line concept will be introduced as shown in figure 38 below. Reducing the number of configurations, categorizing of different configurations based on the expert interview, and Product-process matrix was developed for each configuration. Based on the product process matrix the layout and adaptive tools are selected.

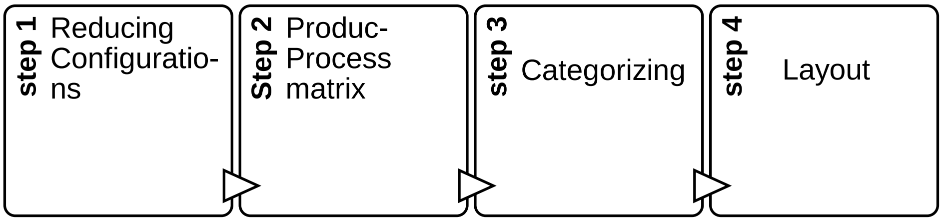


Figure 37: Concept workflow. Source: Own illustration.

3.1. E-axles configuration

As shown earlier in section 2.1 there are more than one possible configuration for the e-axles based on the different variants. Studying the different configurations are required to define the assembly line layout, machines and tools.

3.1.1. Expert interview

An expert interview was required to reduce the number of possible configurations and variants based on the company's design preferences. Qualitative analysis for the frequency of the different features' usage was done by asking the experts to provide ratings as shown below in table 3. Based on those ratings, the configurations that are always used and frequently used will be considered for product-process analysis. [63]

Table 3: Qualitative rating scale

Rating	Always used	Frequently used	Less frequent used	Rarely used	Never used
Score	4	3	2	1	0

The shifting features were discussed, and the frequently used shifting is the single speed, and the double speed. Multiple speeds shifting is rarely used as shown.

The experts mentioned that the helical two-stage transmission is frequently used, and planetary single and double stage are less frequently used. Helical single stage and multiple gears are rarely used by their side.

The differential type used frequently based on the expert interview is the conventional bevel gear differential. The other features were rarely used.

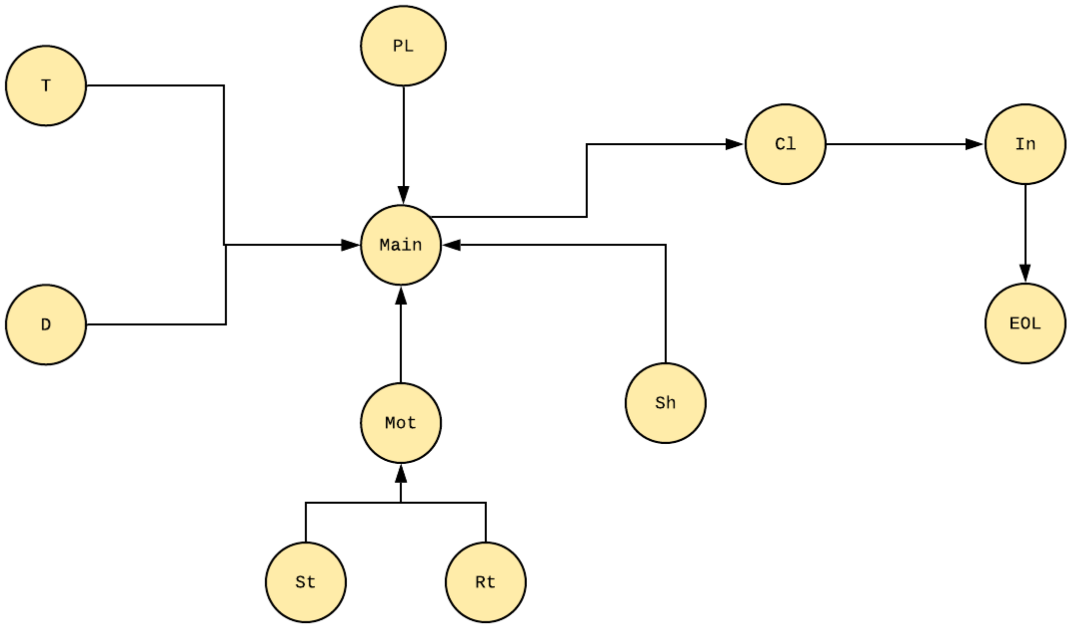
There was more than one cooling method used for the cooling of the e-motor as mentioned by the experts. The stator cooling is an always-used technique while the rotor forced cooling is less frequently used.

The detailed rating for each variant is shown in Appendix A.

[63] Weinzerl, Jeitler, *et al.* (2019)

3.1.2. Product process Matrix

After conducting the expert interview, the most frequent features were considered as mentioned in section 3.1.1 and a detailed product-process matrix was conducted. The product process matrix is a technique used to categorize the products based on the processes required to produce those products. In this thesis, the product process matrix will be used to analyse the processes required to assemble each configuration/variant. Moreover, this matrix will be used to have a solid document with the whole processes required in order to determine the machines needed (detailed matrix in appendix E). To visualize the assembly overview is developed as shown below in figure 38. [64]



T → Transmission	D → Differential	St → Stator
Rt → Rotor	Mot → e-motor	Sh → Shifting
Cl → Closing	In → Inverter	EOL → End of line

Figure 38: E-axle assembly overview. Source: Own illustration

[64] Safizadeh, Ritzman, *et al.* (1996)

The transmission, differential, e-motor, shifting and parking lock are pre-assembled independently. The e-motor is either custom made, or stator and rotor need to be pre-assembled. The main assembly is the assembly of the main components, and then closing is the step of sealing and closing the main assembly. Inverter is attached after the closing step is finished then end of line tests are conducted. The most frequently used processes to produce each variant is considered for further analysis. Based on the product-process matrix in appendix E, the summarized components and processes required for each step is shown below in table 4-8.

Table 4: Transmission and motor step

Transmission		**Motor**	
Components	**Processes**	**Components**	**Processes**
Planet Carrier	Interference fit by pressing	Stator	Interference fit by pressing
Ring gear	Interference fit by shrinkage	Rotor	Interference fit by shrinkage
Shafts	Assembly	Sealing	Centring
Gears	Bolting	Sensors	Assembly
Bearings	-	Bearings	Bolting

Table 5: Stator and Rotor step

Stator		**Rotor**	
Components	**Processes**	**Components**	**Processes**
Housing	Interference fit by pressing	Core	Interference fit by pressing
Cooling	Interference fit by shrinkage	Shaft	Interference fit by shrinkage
Stator	Gluing	Bearing	Centring
-	Bolting	Core	Interference fit by pressing
Housing	Interference fit by pressing	Shaft	Interference fit by shrinkage

Table 6: Shifting and Differential step

Shifting mechanism		Differential	
Components	**Processes**	**Components**	**Processes**
Hub	Assembly	Sub Assembly	Assembly
piston	Bolting	Ring gear	Bolting
shaft	-	-	-
motor	-	-	-

Table 7: Parking lock and Main step

Parking lock		Main	
Components	**Processes**	**Components**	**Processes**
Ratchet	Preparation of parts	Sub-Assemblies	Assembly
Fork	-	Parking lock parts	Bolting
Small parts	-	spacers	measurement

Table 8: Closing and sealing step

Closing		Sealing	
Components	**Processes**	**Components**	**Processes**
Main	Bolting	radial shaft	Interference fitting by press
Sealing	sealing	labyrinth	apply sealant
-	-	gasket	assembly
-	-	sealant	-

The tables show the different most frequent possible components for each assembly step as well as the most frequent possible processes used. This step will facilitate the categorizing process during the development of the layout.

3.2. Layout

After analysing the different configurations of e-axles and developing the product process matrix for each component, the machines, adaptive technologies and layout need to be selected.

3.2.1. Machines and Tools

An expert in the automotive powertrains industry was interviewed to define the frequently used machines in the automotive industry for each process. The result of the interview is shown below in table 13.[65]

Table 9: Process Machine table

Process	Machine
Interference fit by pressing	Hydraulic press
Interference fit by shrinkage	Induction furnace
Centring process	Centring Device
Bolting	Hand tools / Bolting cobot,
Sealant apply	Sealing cobot
Measuring clearances	Measurement tools
End of line tests	EOL testing machine

The interference fitting is done by a hydraulic press machine where the parts placed in the machine and a fixture is used to assemble the second part by force. The interference fitting by shrinkage is done by heating the first part, so the part dimensions are bigger due to temperature expansion coefficient. The parts are assembled freely and then interference fitting occurs when the heated part cools down.

The airgap between the rotor and stator need to be maintained equally along the circumference. A centring device is used where the rotor is inserted concentrically to the stator.

Bolting cobot is a collaborative robot with human and used for the bolting process of the closing station along with the sealing cobot used to apply the sealant as shown below in figure 39. [66]

[65] Bloder (2019)
[66] Robots[Online]. Available: https://www.universal-robots.com/products/

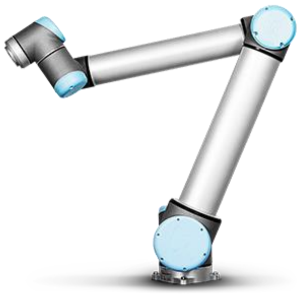


Figure 39: Cobot. Source: Universal robots online source on 28.10.2019

3.2.2. Categorizing

Categorizing of the assembly steps into stations is performed using the Product process matrix and assembly overview illustrated earlier. The categorizing method was based on the following:

- Categorize components based on the degree of similarity of processes required for assembly
- Categorize components based on the e-axle's assembly flow

. Table 14 below shows the categorizing of steps to stations.

Table 10: stations categorizing

No.	Station	Function	Processes	Machines
1	Transmission Pre-Assembly	Preassembly of shafts, Gears and Bearings	Interference fitting Placing snap tings and nuts	Hydraulic press Induction furnace Hand tools
2	Motor Pre-Assembly	Housing pre-assembly Small parts installation Cooling assembly	Interference fitting Bolting	Hydraulic press Induction furnace Hand tools
3	Motor Assembly	Rotor Stator Assembly of Rotor and stator	Interference fitting Centring	Hydraulic press Induction furnace Centring device
4	Main Transmission Assembly	Installation of shafts	Interference fitting Bolting	Induction furnace Hydraulic press

		Park lock assembly Shifting assembly		Measurement tools Hand tools
5	Closing station	Closing of Main assembly Assembly of inverter	Sealing Bolting	Sealing cobot Bolting cobot
6	End of Line Testing	Test e-axles at end of line based on testing requirements	Connect Disconnect	End of line testing machine
7	Rework station	Rework defected e-axles	-	Hand tools Access to stations machines

Where station 1 is producing the pre-assembly of shafts, gears and bearings, as those components. Station 2 is producing the motor housings with the small parts installation (oil guides) and cooling assembly. Station 3 is producing the motor through assembly of rotor and stator. Station 4 is producing the Main transmission through assembly of pre-assembled shafts, shifting assembly and park lock. Station 5 is producing the e-axles by closing and sealing the e-axle and finally the end of line station tests the e-axles according to the requirements. Rework station is introduced where e-axles rework take place.

3.2.3. Layout Design

The straight assembly line and the U-shaped assembly line were studied as shown in section 2.3. The U-shaped assembly line is used when there is a high product and process variety compared to the straight assembly line which is suitable for fixed product and processes. As the aim of this project is to design an assembly line suitable for producing high variety of products (e-axles), the U-shaped assembly line layout is considered. [67]

Based on the assembly flow shown earlier, initial U-shaped layout was developed as shown below in figure 40.

[67] Sirovetnukul and Chutima (2010)

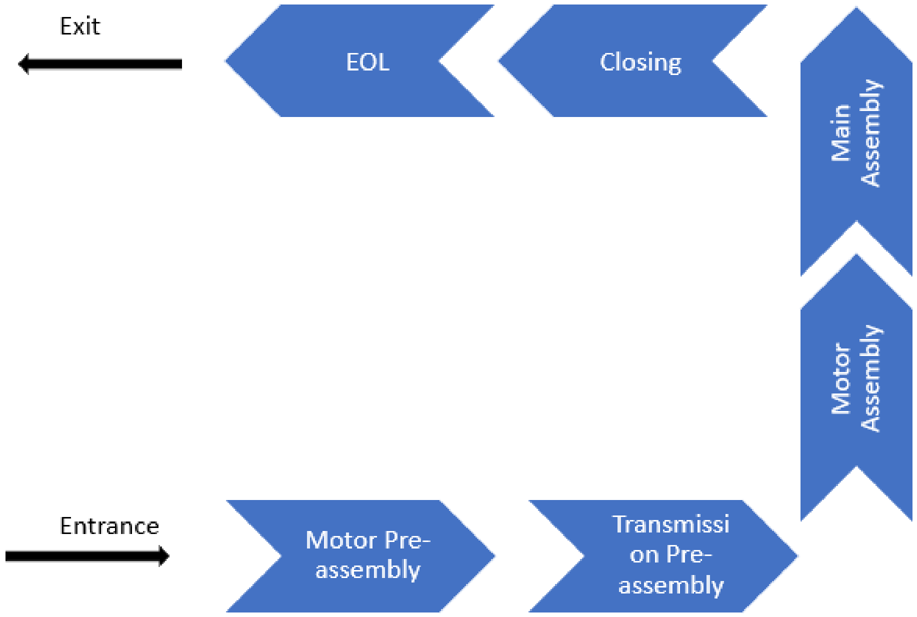


Figure 40: U-shaped layout. Source: Own illustration.

The initial design was further analysed, and it resulted in the following:

- The transmission pre-assembly is totally independent than the motor pre-assembly, and parts need to pass by the transmission pre-assembly in this layout
- A bypass subline is required for the motor preassembly and transmission pre-assembly

A second layout optimization was conducted to eliminate the bypass subline required, and figure 41 below shows the optimized layout.

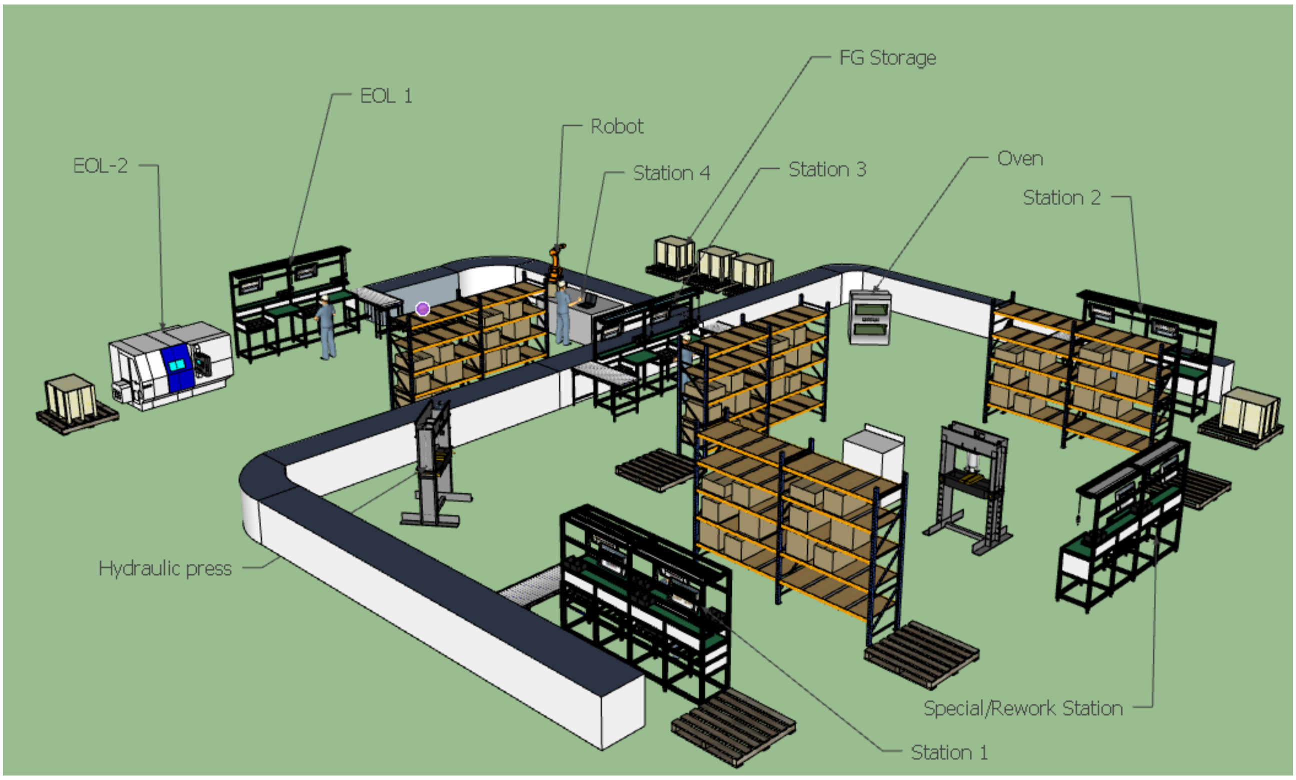


Figure 41: Optimized U-shape assembly line. Source: Own illustration.

The parts are going in parallel from the two sides of the U-shaped assembly line to the motor pre-assembly and transmission pre-assembly. The two stations supply the main assembly station with the transmission and motor parts. After assembling of transmission to the motor, the assembly of inverter and closing of e-axle takes place in the closing station. The end of line station performs the different tests required, after the closing of the e-axles.

The layout shown provides the benefit of the worker re-allocation to the different stations as well as having the machines central between the different assembly stations. This allows for higher flexibility and balancing the different stations throughput. The assembly stations are composed of the following main components (for detailed parts, please refer to appendix I):

- Hand tools
- Assembly table for 2 workers
- Fixtures
- Discharge element
- ESD footrest

The assembly table for two workers is used to allow re-allocation at any time in the assembly process without affecting the capacity of the target station. The closing station and end of line tests are separated in a separate U-shape line, as the two stations are robotic and machines-based stations. The capacity of closing and end of line stations are not affected by the number of workers but with the number of machines/ robots.

3.3. Productivity and Rework Analysis

The effect of the high product variety on the assembly line can be studied through studying the effect on productivity and rework percentages. Master thesis developed at the Institute of Production Engineering-TU Graz by Mr. Muaaz Abdul Hadi studied the effect of high product variety on assembly lines. This thesis was used as a base for studying the effect on productivity and rework percentages of the e-axle assembly line as shown in the figure 42 below.[68]

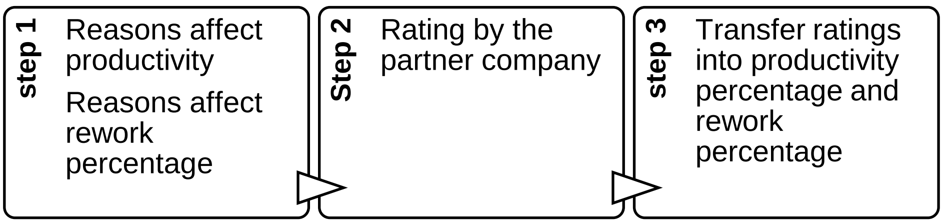


Figure 42: Analysis steps. Source: Own illustration.

3.3.1. Failure modes

In this thesis, there is a distinction between productivity failure modes and rework failure modes and defined as:

- Productivity failure modes: they are the failure modes which make the worker works slower than defined. This results in a lower throughput
- Rework failure modes: they are the failure modes which make the worker assemble the e-axle not in the correct way. This results in a rework of the e-axle

The different failure modes were categorized into three main categories which are:

- Information: where potential failures related to assembly instructions are defined

[68] Abdul Hadi (2019)

- Assistive operations: where potential failures related to the lack of assistive technologies
- Person related: where the potential failures related to the worker are identified

The main failure mode in each category was defined, and the result is eight potential failures which affect the worker productivity: [69]

- Poor process description- missing information: The aim of the assembly line is to produce e-axles with a lot size of 1, poor assembly process description is a high potential failure because of the high number of configurations to be assembled
- Searching for parts and tools: as different e-axles configurations are assembled and different tools and parts are picked, there is a high potential for searching for parts and tools affect the station / worker productivity
- Wrong part and tool used: as different e-axles configurations are assembled and different tools and parts are picked, there is a medium potential for wrong picking of parts and tools
- Over controlling / planning: over controlling and planning has a medium potential failure as the worker in many cases will be first introduced to a specific configuration
- Missing of immediate guidance: the worker requires immediate guidance has a medium potential because of the high number of configurations
- Wrong judgement of the worker is a potential failure mode as the worker might face a new configuration and misjudge the assembly instructions
- Poor skill level of the worker is a potential failure mode as the worker might be introduced to a new configuration, the worker never assembled before
- Unexpected event is a potential failure mode if an unexpected event occurred which would affect the worker productivity

The same concept was used to define the rework reasons. Extra category is defined for the rework reasons for e-axles than defined earlier in productivity which is the audit. Audit defines the potential rework because of the quality control related policies.

The potential failure modes in each category were defined, and the result is eight main potential failure modes which affect the rework percentage: [70]

- Poor process description- missing information: The aim of the assembly line is to produce e-axles with a lot size of 1, poor assembly process description is a high potential failure because of the high number of configurations to be assembled
- Wrong part and tool used: as different e-axles configurations are assembled and different tools and parts are picked, there is a medium potential for wrong picking of parts and tools
- Missing of immediate guidance: the worker requires immediate guidance has a medium potential because of the high number of configurations
- Missing in process quality check: as different e-axles` configurations are assembled; some configurations require quality specific checks. The worker has a high potential of missing any of these checks during assembly
- Negligence of instructions due to confidence/ fatigue: The expert mentioned negligence of instructions is a typical failure with experienced workers
- Poor skill level of the worker is a potential failure mode as the worker might be introduced to a new configuration, the worker never assembled before

[69] Klaus (2019)
[70] Klaus (2019)

- Wrong judgement of the worker is a potential failure mode as the worker might face a new configuration and misjudge the assembly instructions
- Lack of prevention measures is a potential failure mode as there is no fixed monitoring system due to high product configurations to be assembled

3.3.2. Rating

The reasons for productivity effect and rework percentage were sent to the partner company to be rated. The rating is based on two parameters severity and occurrence:

- Severity: shows how severe is the effect of the potential failure mode on the productivity and rework percentages. The rating scale provided to the partner company is shown in appendix D
- Occurrence: shows how frequently the potential failure mode would happen during the assembly of the e-axle based on the partner company experience. The rating scale provided to the partner company is shown in appendix B
- Detection: shows how the potential failure mode can be detected. The rating scale provided to the partner company is shown in appendix C

The results of the ratings were received from the partner company, and shown in appendix F and G.

3.3.3. Transfer to Percentage

In order to be able to analyze the effect of each reason on productivity and rework, transferring the rating into percentage is required. These percentages will later be used in the simulation to calculate the reduction in throughput and the number of reworked e-axles. Based on these calculations the e-axle price can be calculated.

The transfer process is done by using the severity scale in appendix C and occurrence scale in appendix B and was done as follow:

- The assembly steps and timings for e-axles shown in appendix P and Q were used to calculate the total number of assembly steps required per e-axle. The calculation was done based on e-axle D which needs 32 assembly steps and average assembly step duration of 267 seconds
- The occurrence rating provided by the partner company is given in occurrence per number of possibilities. The number of possibilities in the transfer process is considered the assembly steps. The rating provides information on how frequent the failure reason occurs per e-axle assembly
- The severity rating provided by the partner company is used to calculate the time needed/ the effect of the failure mode based on table 11 below

Table 11: Severity transfer

severity rating	Duration
10	1 x average assembly step duration
6-9	0.75 x average assembly step duration
3-6	0.5 x average assembly step duration
1-3	0.25 x average assembly step duration

The example below in table 12 for the poor process description shows how the percentages were calculated for the productivity

Table 12: productivity example

Reason	Occurrence rating	Severity Rating	Occurrence transfer	Severity transfer	Effect on productivity in percentage
Searching for parts and tools	10	6	1 in 20 steps	0.5 x average assembly step duration	2.4%

The transfer equation used is: $\frac{Number\ of\ assembly\ steps}{Occurrence\ transfer}\ x\ severity\ transfer$

The rework percentage is calculated based on the worst-case scenario. The occurrence was only considered, and detection rating was not considered. The severity does not affect the number of reworked e-axles, but the time required to rework the e-axle. The rework percentage transfer is shown below in table 13.

Table 13: Rework transfer

Reason	Occurrence rating	Occurrence transfer	Occurrence percentage
Wrong part/ tool used	6	1 in 120 steps	0.8%

The different failure modes were calculated based on the same methodology used in the examples.

3.3.4. Adaptive technologies

The adaptive technologies were studied in section 2.2, only technologies with high readiness level is considered as the development of the assembly line that would take place in 2020.

The following technologies were considered to analyze the potential reduction of the failure modes:

- Static screen technology
- Pick to light technology (PTL)
- Pick to voice technology (PTV)
- Hybrid PTL/PTV technology

The effect of the adaptive technologies is studied for the potential failure modes affect productivity and rework of e-axles

Searching for parts/ tools is used to illustrate the methodology used to calculate the benefits for each technology.

- Static screen technology would reduce the occurrence and severity of this failure mode as using visualized instructions the part/tool shape can be shown as well as instructions for location
- Pick to light (PTL) technology has high effect on the occurrence and severity of this failure mode. The system flashes at the right part/tools need to be picked by the worker
- Pick to voice (PTV) technology would reduce the effect of this failure mode as it guides the worker to the part place. There is still an effect on productivity because of the time needed by the worker to locate the part and to listen for instructions
- Hybrid system allows for the highest productivity gain because of the combined use of PTL and PTV

The effect for each reason is considered using the same methodology and using the same percentage calculation illustrated in section 3.3.3. The benefits for each technology are shown below in figures 43 and 44.

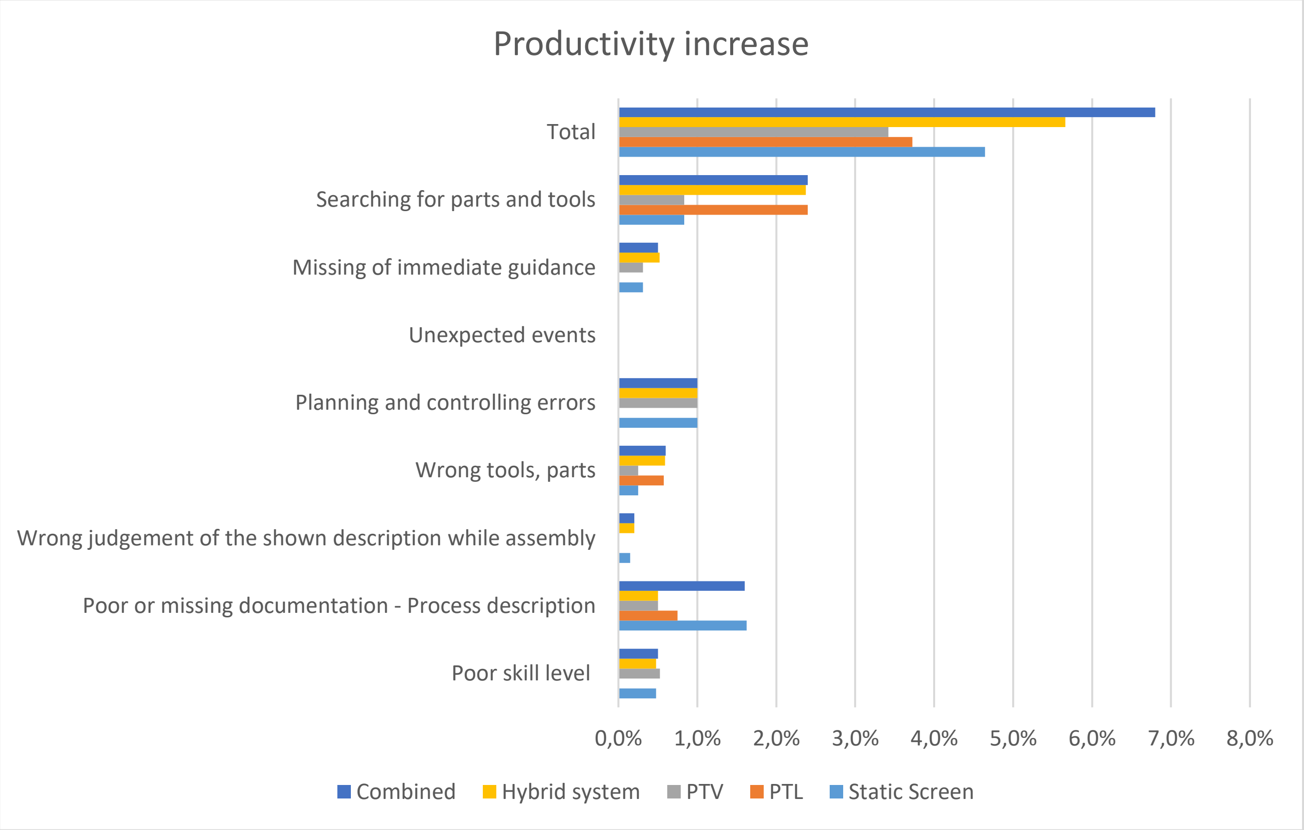


Figure 43: Productivity increase. Source: Own illustration

The hybrid system has a high potential for increasing the productivity with 5.7%, follows is the static screen technology with 4.6%. Moreover, static screen increases productivity with 3.4% and finally PTL with 3.7%.

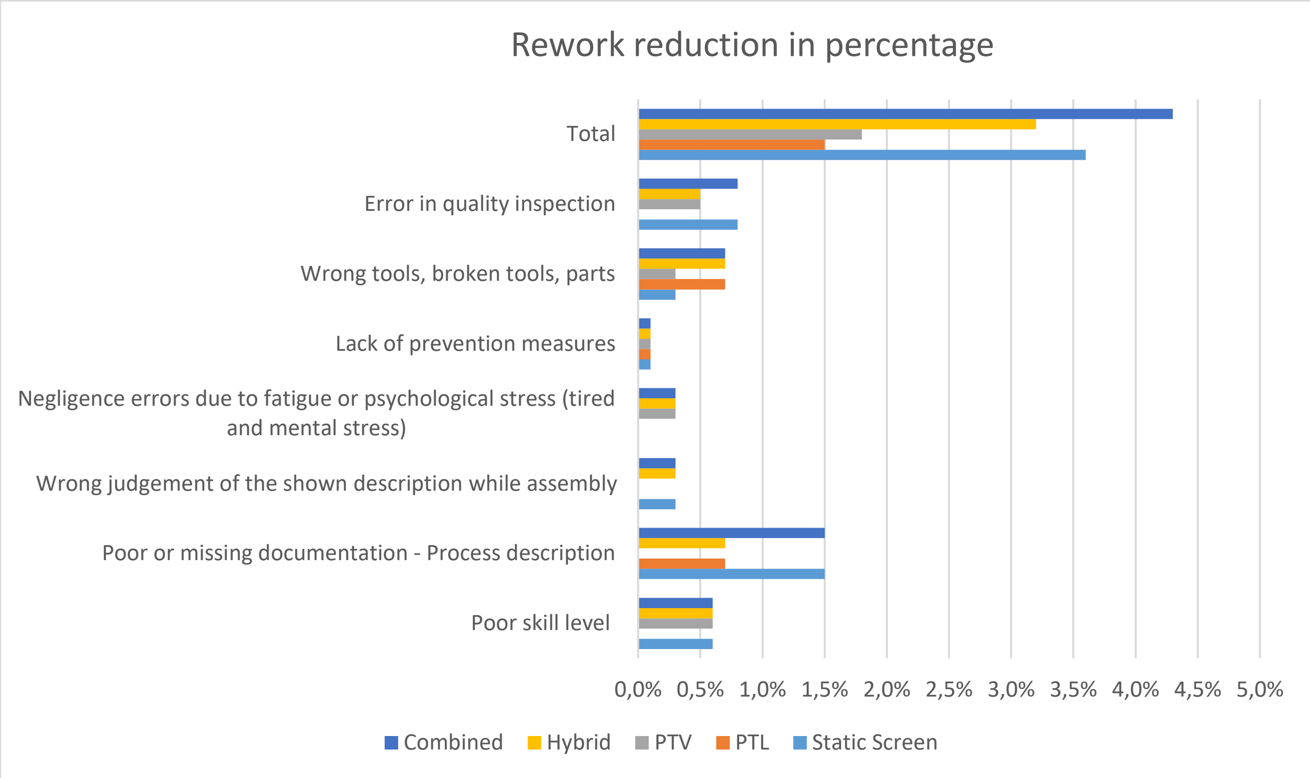


Figure 44: Rework reduction. Source: Own illustration

The rework percentage reduction because of implementing static screen is 3.6%, PTL 1.5%, PTV 1.8% and Hybrid system 3.2%.

The effect of each technology on the throughput and costs are further analysed with the simulation tool Tecnomatix in the next chapters.

4. Tecnomatix Simulation

In order to evaluate the feasibility of the adaptive concepts and layout introduced earlier in the concept section, a simulation model is developed. The following workflow was followed through the work of this thesis as shown below in figure 45.

Figure 45: Simulation Workflow. Source: Own illustration

The workflow tasks represent the different simulations performed. The results are used to provide realistic data for the project stakeholders regarding the feasibility of our proposed layout and technologies where:

- Basic Model: simulate the initial model proposed by the partner company to assess the simulation concept and the accuracy of the results compared to their results
- Layout Model: simulate the initial model proposed to the partner company to evaluate the benefits of the layout compared to the Basic model proposed them
- Layout Optimization: optimize the layout based on the first simulation run
- Adaptive Concepts: simulate the adaptive concepts proposed to the partner company regarding the effect on the throughput
- Axle sequence: simulate the effect of the different e-axle types sequence introduced to the assembly line

4.1. Basic Model

The partner company did previous effort on this project and developed an assembly line concept for assembling e-axle D. The layout of the partner company is shown below in figure 46. [71]

[71] Rampe (2018)

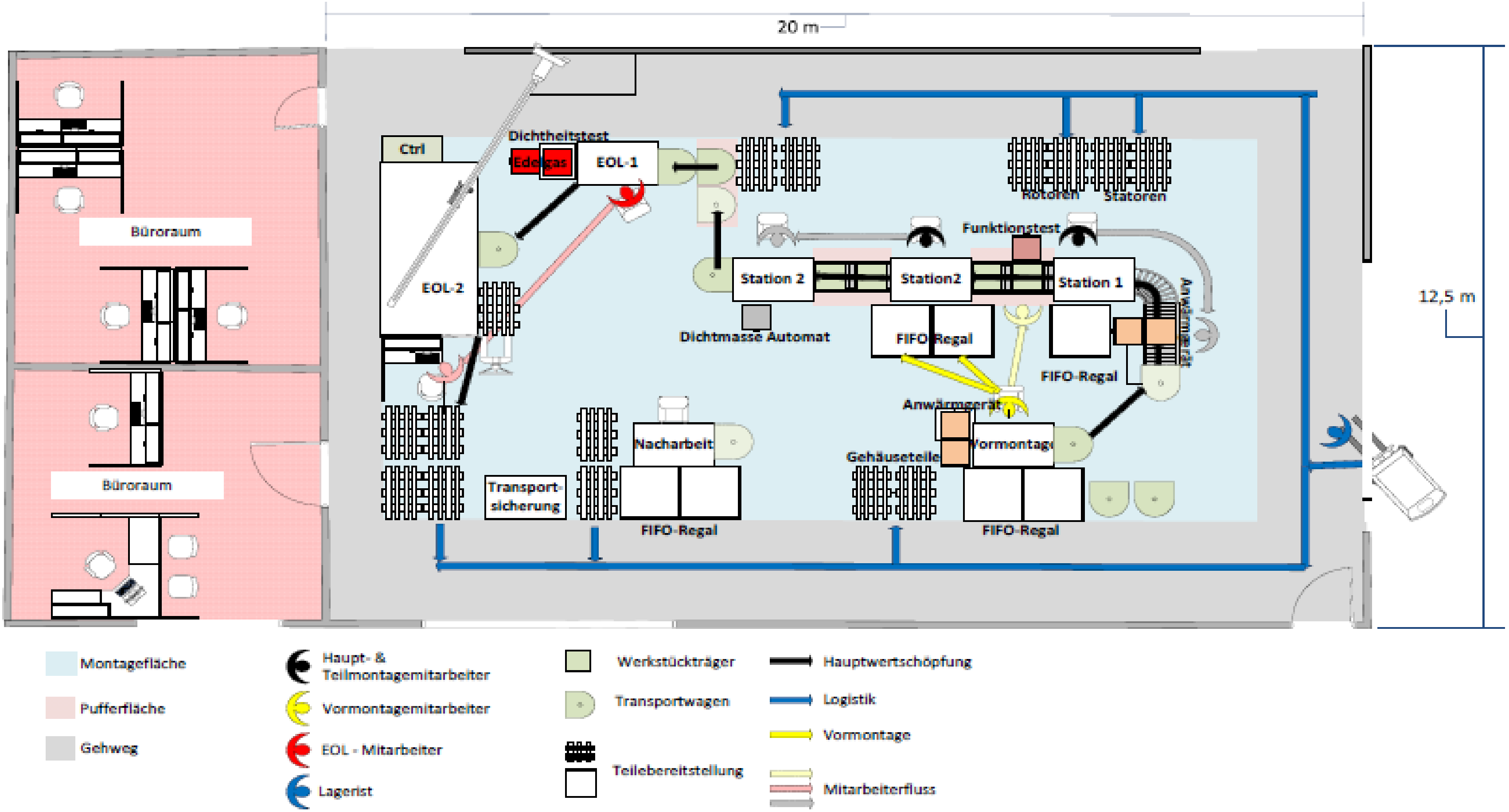


Figure 46: Partner company's Layout. Source: Rampe (2018).

The layout is composed of five stations; three assembling stations, end of line (EOL) test station and rework station. The e-axle production process is done by four workers where the company neglected the rework percentage in this model. Three workers are for the assembly process and one worker for EOL test. Table 14 below shows the distribution of tasks between stations, and for detailed assembly steps and timings refer to Appendix P.

Table 14: Tasks distribution

Tasks / Station	Pre-Assembly	Station 1	Station 2	EOL
Task 1	Housing preparation	Stator	Assembly of Worm wheel	EOL test 1
Task 2	Worm wheel, Inverter Shaft and Intermediate shaft	Centring Rotor to Stator	Assembly of Intermediate shaft and Inverter shaft	EOL test 2
Task 3	Parking lock	-	-	-
Task 4	e-Motor Function Test	-	Sealing	-

The motor's housings are supplied from pre-assembly station to station one by assembly line. The function test is performed by the pre-assembly worker at station one. The worm wheel, inverter shaft, intermediate shaft and parking lock are supplied by the pre-assembly worker to station two. After assembling the e-motor, it is supplied from station one to station two by assembly line. The assembled e-axle is kept in the work in progress area by station two worker then picked by EOL station worker.

The throughput of the layout was calculated to be 4555 e-axles / year based on the bottleneck station time and capacity analysis shown below in figure 47.

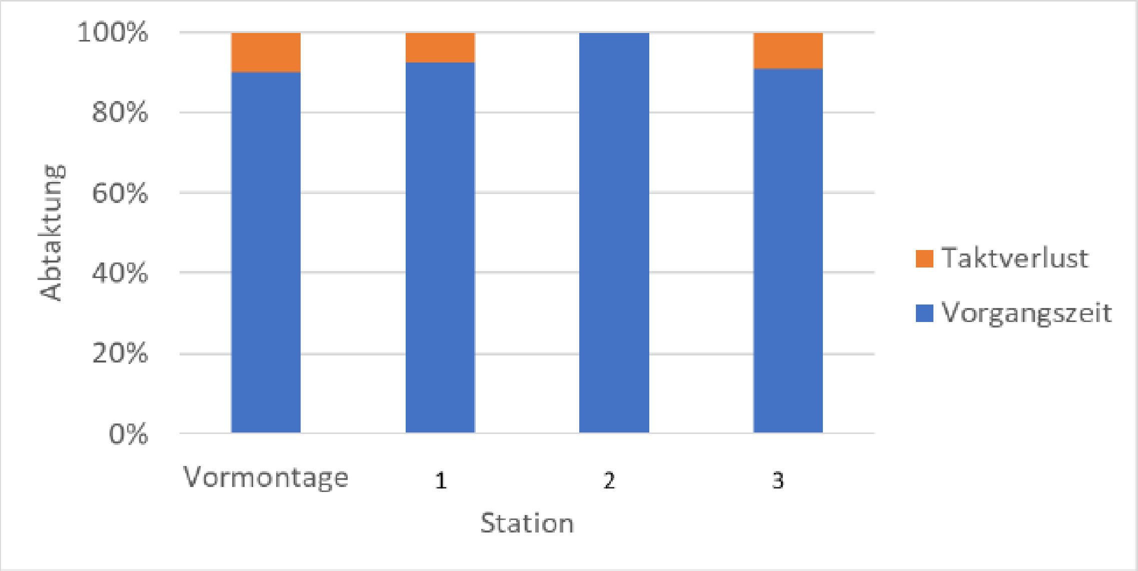


Figure 47: Partner Company's capacity analysis. Source: Rampe (2018).

4.1.1. Simulation model

Simulation model was developed using Siemens Tecnomatix Plant Simulation. The concept of the simulation shown in figure 48 is based on:

- The frames feature in Tecnomatix where each station in the layout is considered as a frame. Inside the frame, each step performed in the station is considered as a station. This concept is used to facilitate the building of the layout by using the basic programmed station blocks of Tecnomatix
- The assembly line speed is neglected as it was not considered in the partner company's calculation for the throughput
- The worker speed between stations is not considered as it was not considered in the partner company's calculation for the throughput
- The machine availability is not considered as it was not considered in the partner company's calculation for the throughput

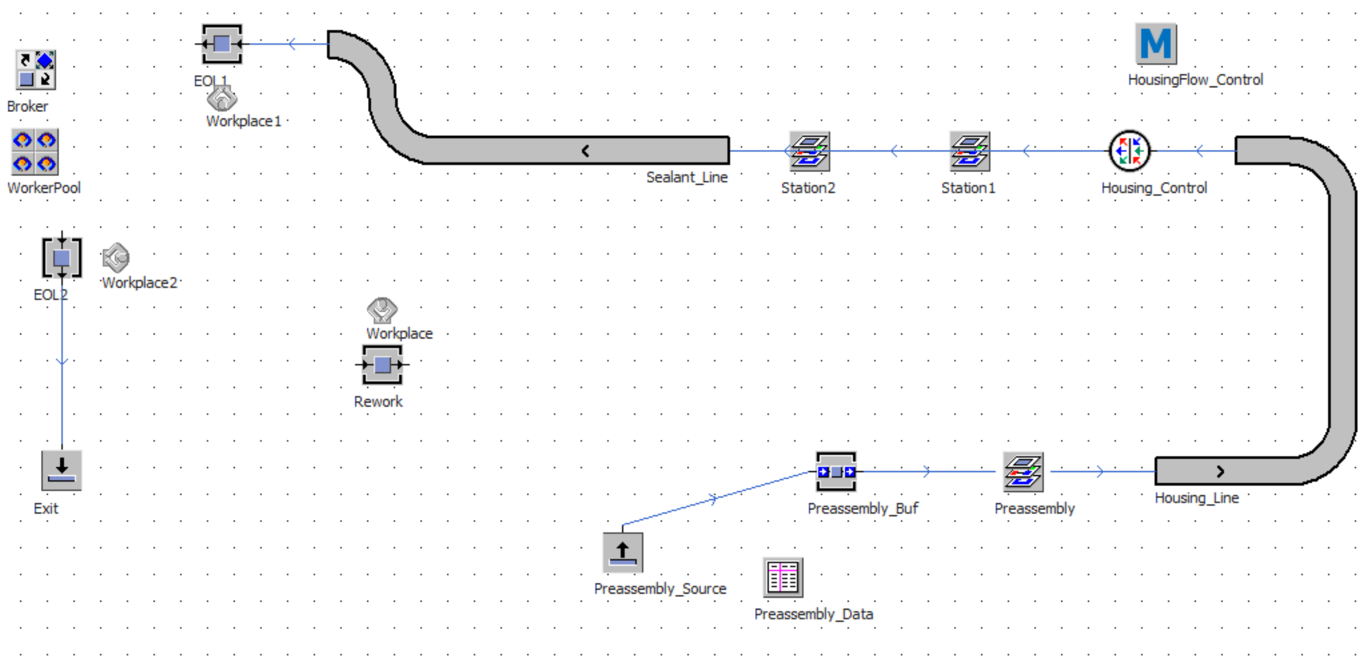


Figure 48: Partner Company's layout simulation mainframe. Source: Own illustration.

The pre-assembly source is creating the parts needed by the pre-assembly station in cyclic sequence based on the material data file inserted to the source function. The material data file is composed of a table with the parts needed and the quantities required in a sequential form.

The Preassembly_Buf is acting as the storing shelves for the pre-assembly station. The parts are created from pre-assembly source to be stored in the pre-assembly buffer, and then enters to pre-assembly station (frame). The pre-assembly frame is shown in figure 49.

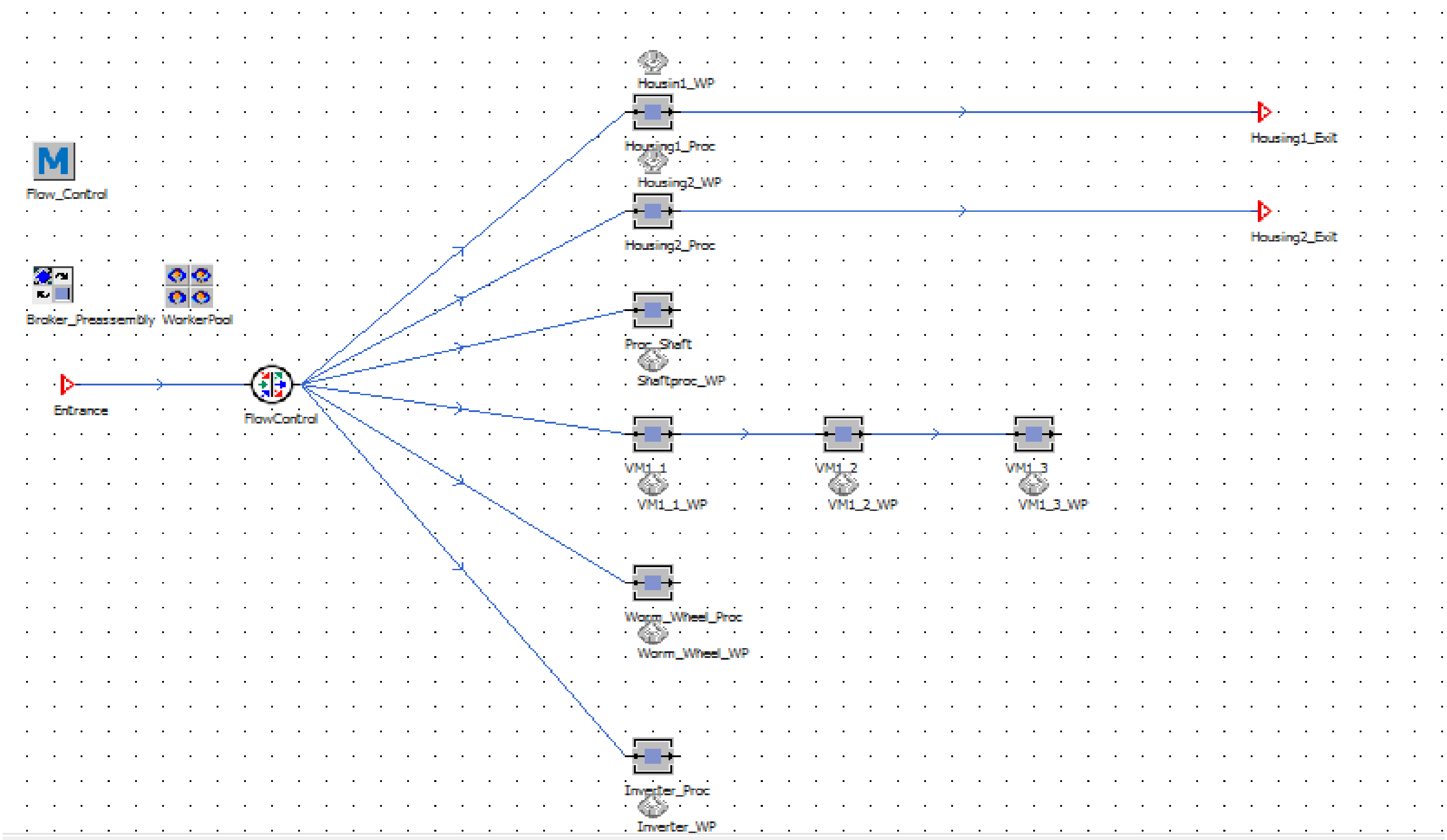


Figure 49: pre-assembly frame. Source: Own illustration.

The pre-assembly frame is composed of material flow control which is responsible for the distribution of the parts to the different assembly steps (represented in the model as a station).

The frame for station 1 is composed of a stator and rotor sources, buffers for the housing parts supplied from station 1 as shown below in figure 50.

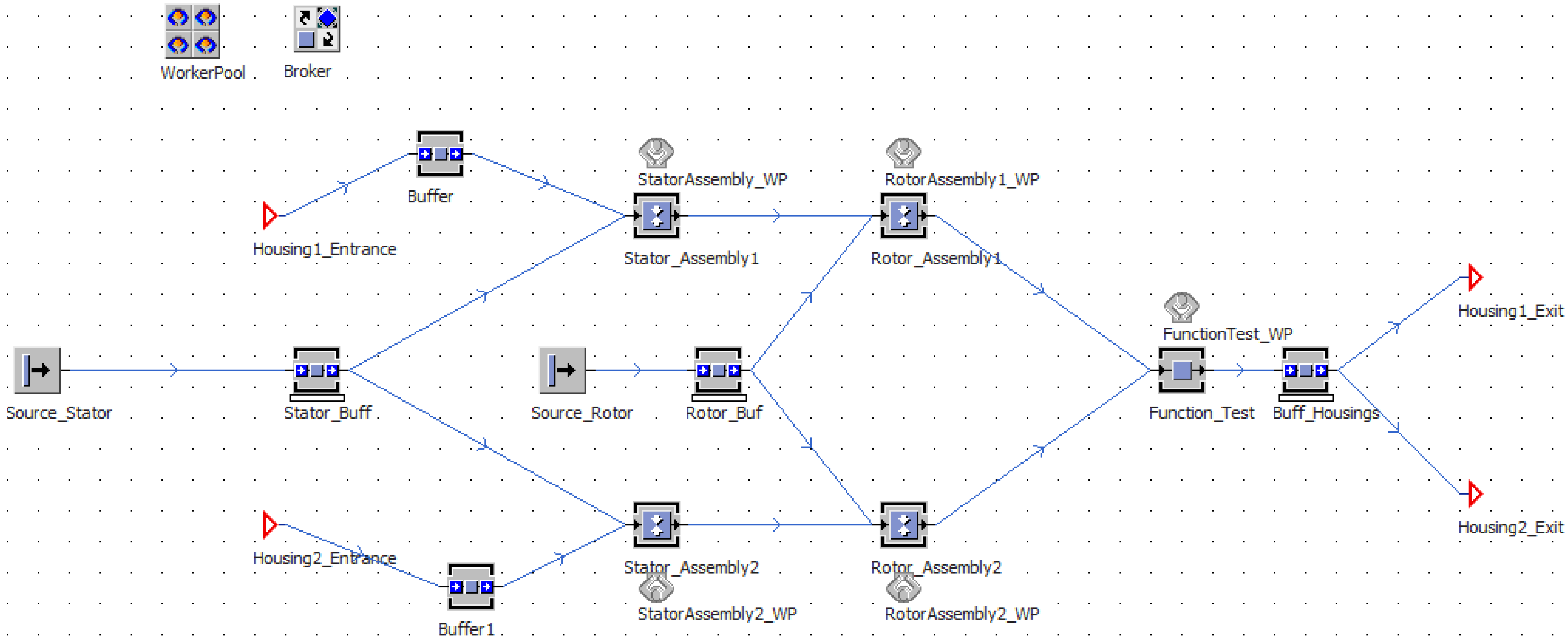


Figure 50: Station one Frame. Source: Own illustration.

Station 1 worker is performing the rotor and stator assembly tasks, and the pre-assembly worker performs the function test.

The station 2 frame is composed of the assembly stations needed to assemble the different parts. The pre-assembly worker supplies the parts from pre-assembly frame and the e-motor supplied by the assembly line from station 1 as shown below in figure 51.

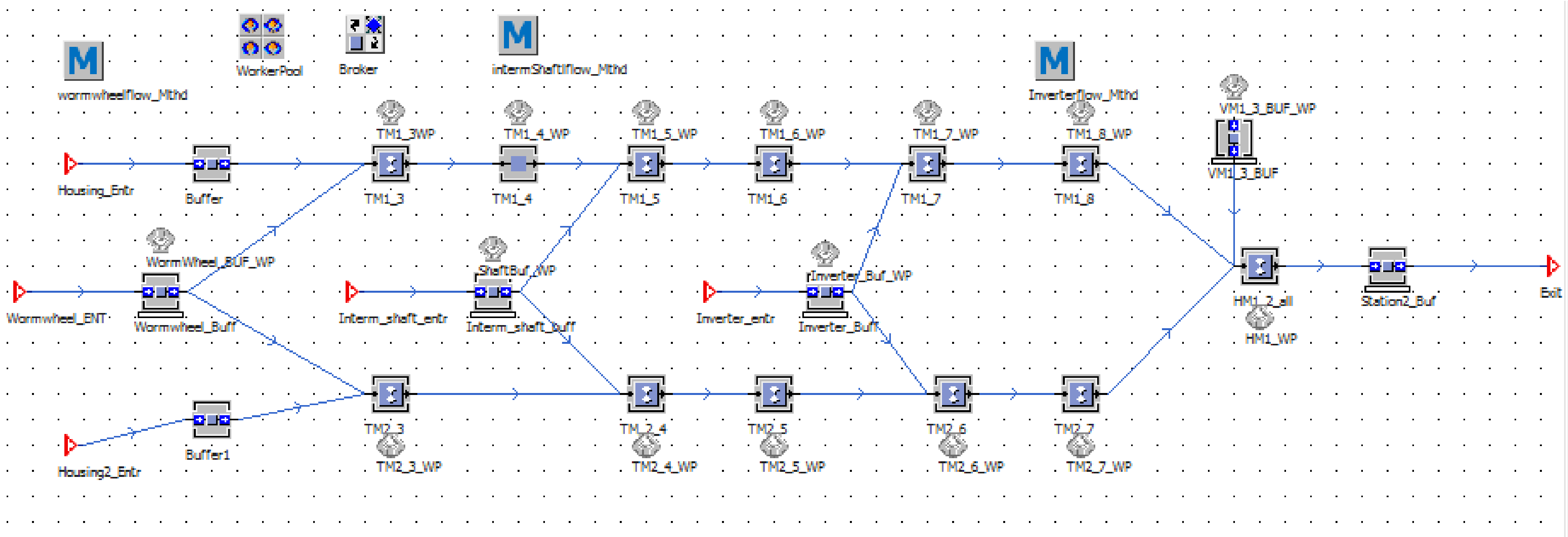


Figure 51: station 2 Frame. Source: Own illustration.

The EOL station is shown in figure 47 where the worker is performing the EOL-1 test, then carries the part to EOL-2

4.1.2. Simulation Results

The throughput obtained from the simulation model after simulating for 1 year is 4532 e-axles / year. The result shows a difference of 0.5% between the simulation model and the calculated throughput.

After analysing the potential reasons for this difference, the following reasons are contributing to that difference:

- The partner company did not consider the walking distance in the calculations. In the simulation model, it was neglected by speeding up the worker movement speed. The movement time of the workers contributes to this difference

- The partner company did not consider the assembly line speed in the calculations. In the simulation model, it was neglected by speeding up the assembly line speed. The line speed contributes to this difference

4.2. Layout Model

The initial layout created after the ideation phase is section 3 is to be modelled. The aim of the simulation model for the initial layout is the following:

- Compare the throughput between the proposed layout by the partner company and the proposed layout in section 3
- Compare the difference in the e-axle price between the 2 different layouts

In order to be able to compare the two layouts, the simulation model is created using the same assumptions used in basic model which are:

- The assembly line speed is neglected
- The worker speed between stations is not considered
- The machine availability is not considered

The layout is composed of six stations as shown below in figure 52.

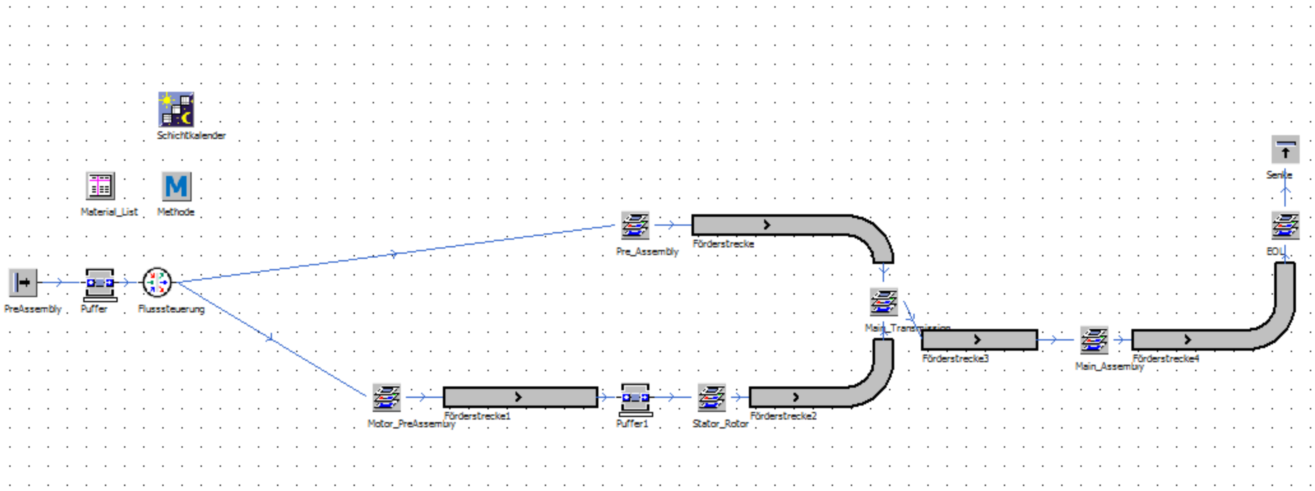


Figure 52: Initial Layout. Source: Own illustration.

The tasks are split between the six stations as shown below in table 15 below:

Table 15: Task distribution Initial layout

Station / Tasks	Pre-Assembly	Motor Pre-assembly	Stator_Rotor	Main_Transmission	Closing	EOL
Task 1	Worm wheel, Inverter Shaft and Intermediate shaft	Housing preparation	Stator	Assembly of Worm wheel	Main assembly	EOL test 1
Task 2	Parking lock	-	Centring Rotor to Stator Function test	Assembly of Intermediate shaft and Inverter shaft	Sealing	EOL test 2

Using the same concept of frames introduced in the basic model, the different stations are considered as a frame. The tasks performed by each station is considered as a station inside the frame in the model.

After running the simulation for the same period of 1 year and including the same calendar used for the basic model of 205 working day/year. The throughput/year is 2484 for a single shift and 4969 for a double shift. The capacity analysis through the simulation of one year is shown below in figure 53.

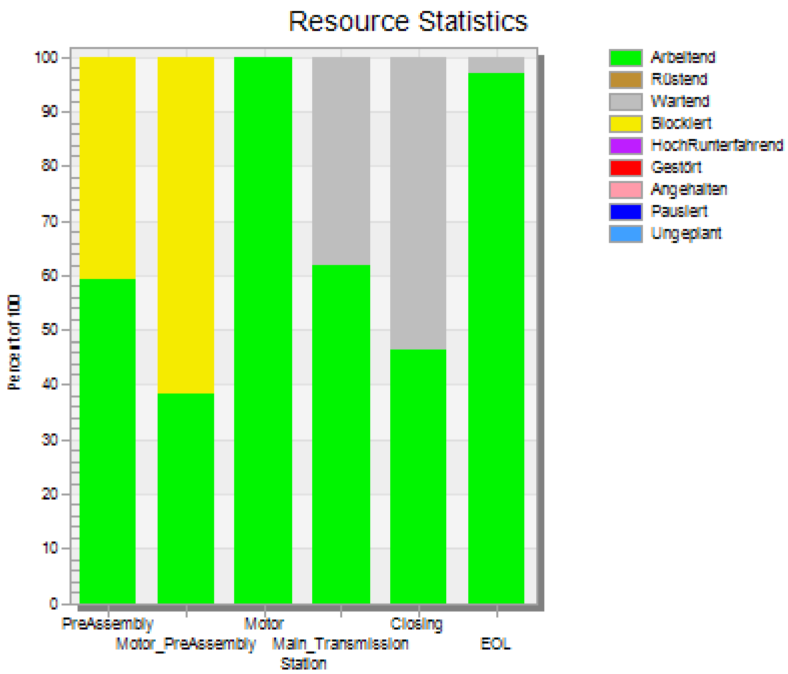


Figure 53: Capacity analysis for initial layout. Source: Own illustration.

From capacity analysis, the motor station is the bottleneck, and Motor_Preassembly station has the lowest efficiency of 37% working and 63% blocked. The average efficiency of the whole stations is 66.5%. This showed that there is a higher throughput potential using the proposed layout compared to the optimized layout proposed by the partner company.

The aim of this thesis is to develop a layout for assembling different e-axles on the same assembly line. Second e-axle with assembly steps and timings was requested from the partner company to be simulated. Simulation model was developed for both e-axles D and L with a capacity percentage of 50% for e-axle D and 50% for e-axle L. The concept of the model is using the same frames concept with the same considerations mentioned earlier. The assembly overview for e-axle L is shown below in figure 54 (details in appendix Q).

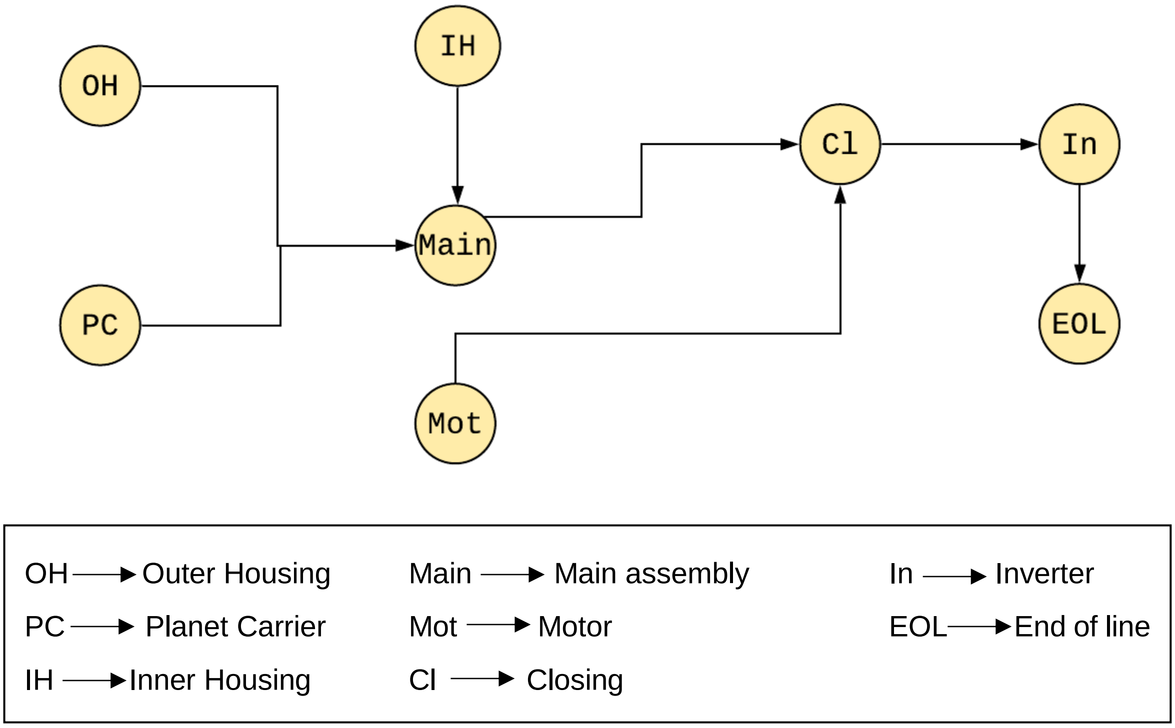


Figure 54: Assembly flow of e-axle L. Source: Own illustration.

The outer housing, planet carrier and inner housing are pre-assembled, the motor is custom made by a supplier. The assembly of outer housing with planet carrier and inner housing take place, and then the custom-made motor is assembled with the housing sub-assembly. The electronics are assembled, and end of line tests are performed.

The results showed a throughput/year of total 2523 e-axles based on a single shift model. The total throughput is 50% e-axle D and 50% e-axle L. Capacity analysis was performed using Tecnomatix to check the bottlenecks as shown in figure 55.

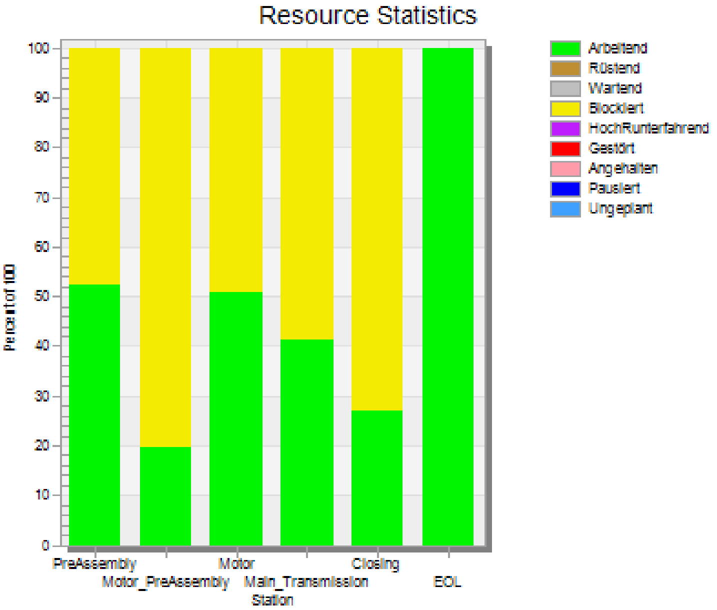


Figure 55: capacity analysis for e-axles D and L. Source: Own illustration.

From the capacity analysis the following can be realize:

- EOL station is the bottleneck for the two e-axles
- The average efficiency of the whole stations is 48.5 %
- Optimization is required to reduce the number of stations and increase the efficiency of the different stations.

4.3. Optimized layout

Optimization effort was spent on the initial layout to increase the average efficiency. Redistribution of assembly steps between stations was performed as well as combining two stations in one station to save the extra cost of one station. The layout of the optimized layout is shown in figure 56 and the distribution of tasks is shown in table 16.

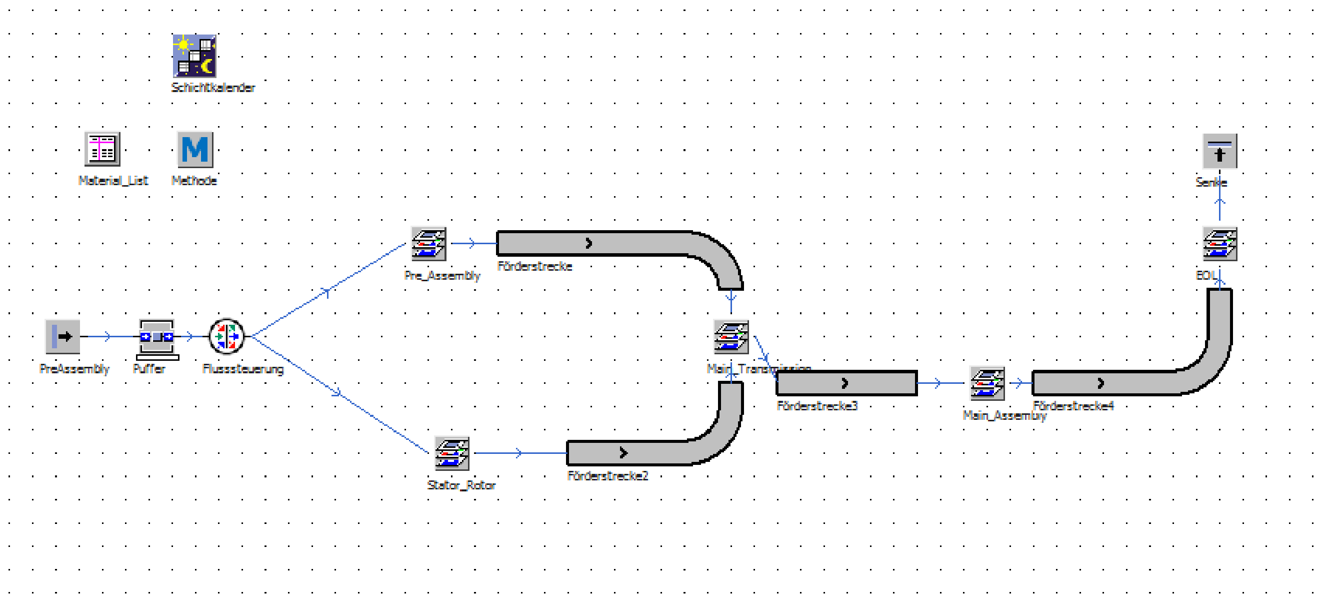


Figure 56: Optimized layout. Source: Own illustration.

Table 16: steps distribution for the optimized layout

Tasks	Pre-Assembly	Stator_Rotor	Main_Transmission	Closing + EOL 1	EOL 2
Task 1/Axle A	Worm wheel, Inverter Shaft and Intermediate shaft	Pre-assembly motor	Function test Assembly of Worm wheel	Main assembly + Sealing	EOL test 2
Task 2 /Axle A	Parking lock	Centring Rotor to Stator	Assembly of Intermediate shaft and Inverter shaft	EOL test 1	-
Task 1 /Axle B	Preassemble Housing	-	Assembly outer housing	Main assembly + Sealing	EOL test 2
Task 1 /Axle B	Pre-assemble Planet carrier	-	-	EOL test 1	-

Simulation run was performed using the same conditions introduced earlier for the basic model and using the same calendar.

The results showed a throughput/year of total 3864 e-axles based on a single shift model. The total throughput is 50% e-axle D and 50% e-axle L. capacity analysis was performed using Tecnomatix to check the bottlenecks as shown in figure 57.

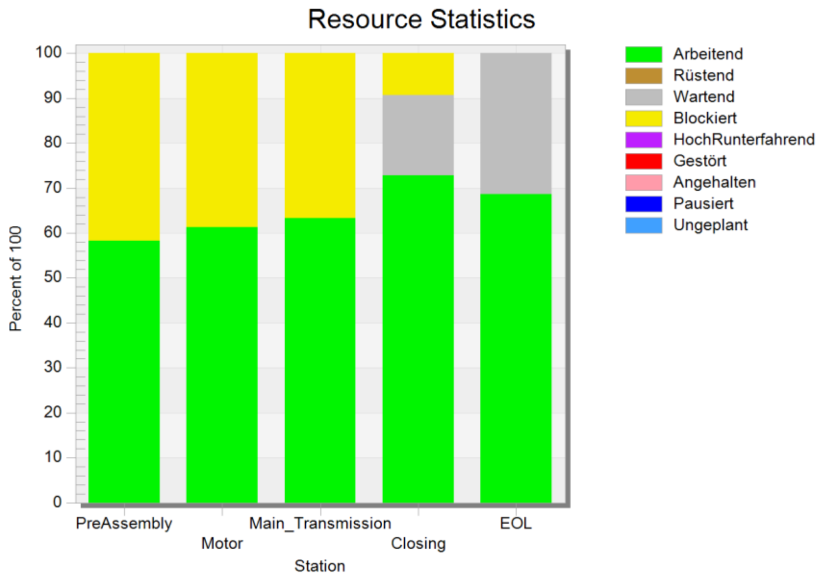


Figure 57: Capacity analysis for optimized layout. Source: Own illustration.

The average efficiency of the layout is 64%. The optimization resulted in 15.5% higher efficiency than the initial layout. The partner company found the optimized results are acceptable.

3D schematic layout for the optimized assembly line is created using SketchUp software as shown below in figure 58.

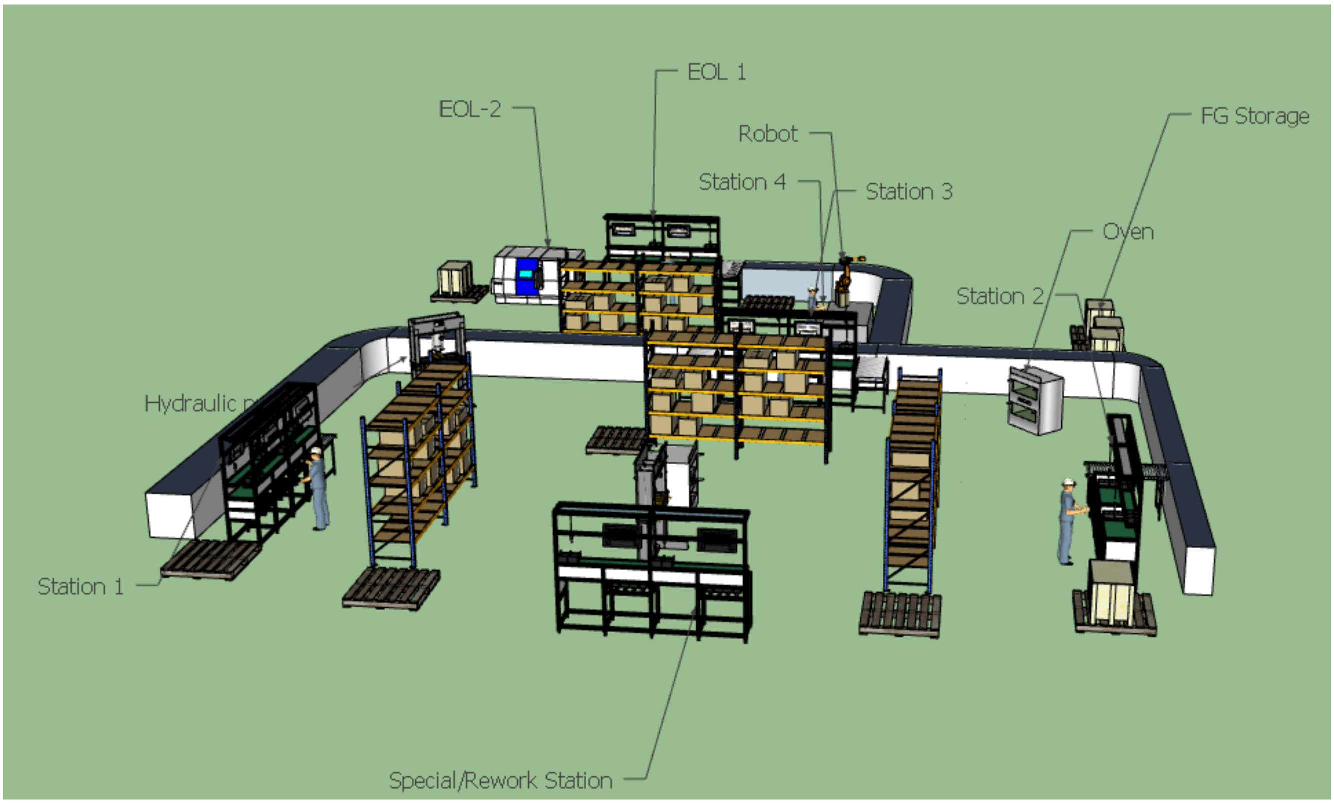


Figure 58: 3D schematic. Source: Own illustration.

4.4. Adaptive Technologies

As part of the project, the adaptive concepts effect of the yearly throughput is to be studied. Simulation model for the optimized layout is modified to apply the effect of the adaptive concepts through productivity of the worker and the rework percentage. The worker productivity and rework percentage are calculated based on the FMEA introduced earlier. A summarized table for the productivity and rework percentages is shown below in table 17.

Table 17: Adaptive technologies effect

factor / Technology	Increase in productivity %	Decrease in rework %
Static screen	4.6%	3.6%
Pick to Light	3.7%	1.5%
Pick to voice	3.4%	1.8%
Hybrid system	5.7%	3.2%
Combined technologies	6.8%	4.3%

First simulation run is done using the worker productivity of 90% and rework percentage of 7%, then different runs were performed for each technology. A final simulation run is performed with the total effect of the simulation technologies.

The effect of the productivity is not same across the different stations, as some steps are not affected by the adaptive technologies with the same degree. A summarized table is shown below in table 18 for the different stations' efficiency based on the combined technologies scenario.

Table 18: station's increase in productivity

factor / Station	Increase in productivity %
Pre-assembly	6.8%
Motor	5%
Main Transmission	6.8%
Closing station	6%
EOL	4%

Pre-assembly and main transmission stations are based on the manual assembly of the worker, so those stations have the higher effect of technologies. Motor, closing station and EOL are based on machines, robots and fixtures, so the effect of technologies is lesser.

The increase in productivity is done in the model through the worker efficiency feature in Tecnomatix. The throughputs resulted from the different simulation runs are shown in table 19.

Table 19: Adaptive technologies throughput

Technology \ Throughput	Non-reworked e-axle/year	Reworked e-axles/year	Total throughput
Static screen	3887	154	4041
Pick to Light	3768	238	4006
Pick to voice	3771	224	3995
Hybrid system	3910	172	4082
Combined technologies	4004	90	4094

4.5. E-axles Sequence

The effect of e-axles sequence was requested to be studied by the partner company. The sequence of the e-axles introduced to the assembly line is affecting the learning curve of the worker for assembling specific e-axle. If the worker is only assembling one e-axle, the productivity will be higher than assembling more than one e-axle and by result the rework percentage will decrease. Based on this the sequence of the e-axles will simulated by changing the productivity of the worker and the rework percentage.

Different scenarios required to be simulated by changing the production percentage of e-axle D to e-axle L and changing the sequence of e-axles introduced as in table 20 below.

Table 20: e-axles Sequence

Sequence \ factor	Increase in productivity %	Rework %
D-D-L-L	7.5%	2%
D-L-D-L	6.8%	2.2%
D-D-D-D-L-L-L-L	8.5%	1.6%
D-D-D-L-L-L	8%	1.8%
D-D-D-L	7.75%	1.9%
L-L-L-D	8.25%	1.7%

Different simulation runs were performed based on the given sequence with the corresponding productivity and rework percentages. The sequence difference was done through controlling the source in the model. Tecnomatix allows for source controlling by defining the sequence of the parts to the system. The results of the simulation runs are presented in figure 59 below.

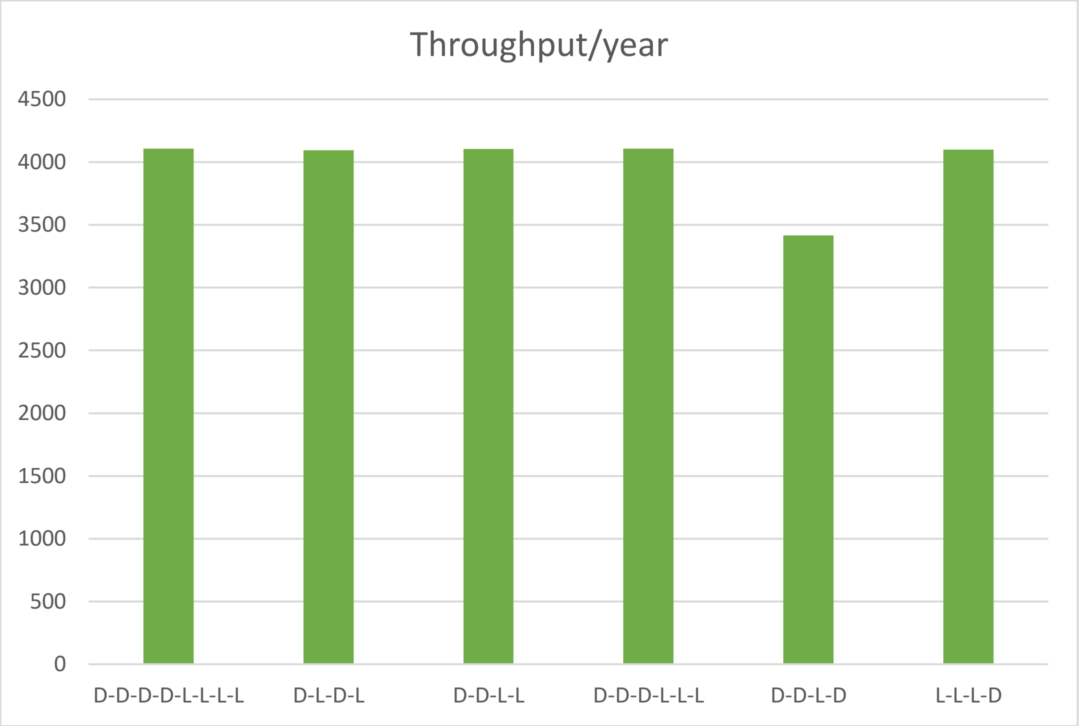


Figure 59: different throughputs of sequence simulation runs. Source: Own illustration.

5. Axle Cost

One of the project requirements is to provide the partner company with an e-axle price. The e-axle price is to be used for bidding in the customers' projects. Total cost of ownership model is used based on what presented in section 2.5 and inputs from the partner company. The cost model used is shown in figure 60.

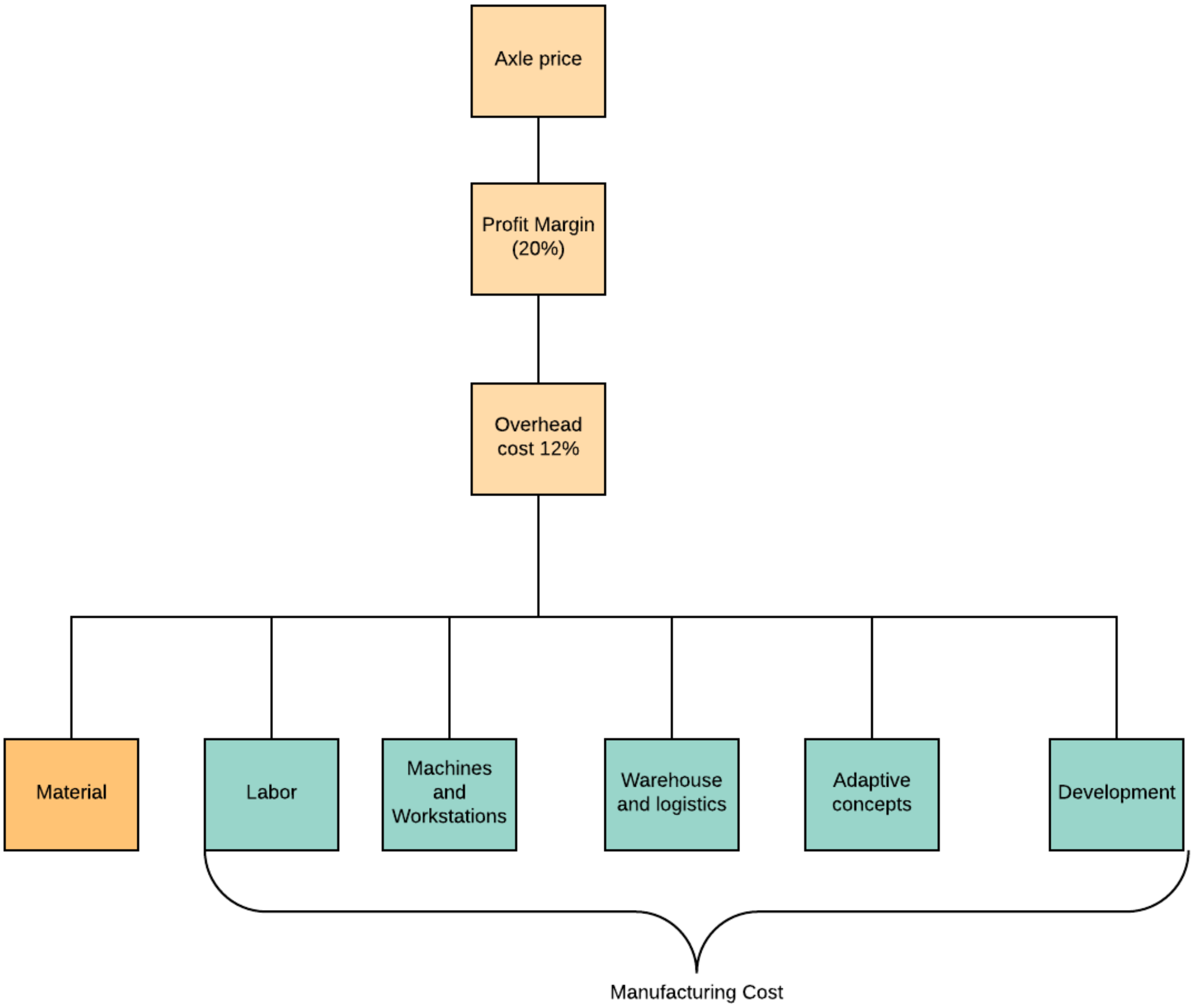


Figure 60: Cost model. Source: Own illustration.

The cost model is composed of three levels of calculations as the following:

- Level one: the base for the calculation are the material, labour, machines, tools and development costs. The calculated costs are used in the next level
- Level two: the calculated costs from level one are used to calculate further costs which is determined by the base costs i.e., overhead costs
- Level three: the profit margin is determined in level three and is calculated based on the market prices and costs from level two

5.1. Material Cost

The material cost is calculated by calculating the direct and indirect costs. The direct costs are the materials which is used directly to the product as the parts, fasteners, etc. The indirect costs are costs associated with the materials used as warehouse costs and scrap. [72]

The model used for calculating the materials cost is shown below in figure 61.

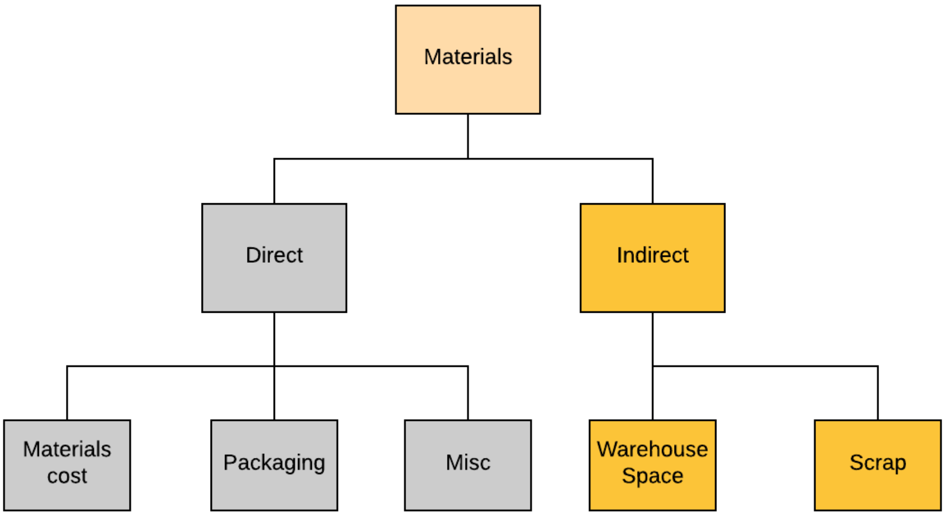


Figure 61: Materials cost model. Source: Own illustration.

The requested data was provided by the partner company for the direct costs and used as shown in table 21 below.

Table 21: Direct material costs

Cost centre	e-axle D	e-axle L
Direct material cost	5,662.00 €	5,500.00 €
Misc.	60.00 €	60.00 €
Packaging	25.00 €	25.00 €
Total Direct Costs	5,747.00 €	5,585.00 €

The indirect material cost is calculated based on warehouse of size 1000m^2, 7.5€/m^2/month and assumed that the warehouse is occupied by 50% e-axle D and 50% e-axle L.

Warehouse cost = $1000 \ x \ 7.5 \ x \ 12 = 90{,}000 \ €/year$.

The scrap percentage was discussed with the partner company, and it was given that scrap percentage of 2% is acceptable. Summarized indirect material costs is shown in table 22 below.

[72] Heilala, Helin, *et al.* (2010)

Table 22: Indirect material costs

Cost centre	e-axle D	e-axle L
warehouse (1000 m^2)	45,000.00 €	45,000.00 €
Scrap (2%)/e-axle	114.94 €	111.70 €

5.2. Labour cost

The labour cost is the cost of the direct labour included in the assembly of the e-axles. The model in figure 62 shows how the labour cost is calculated.

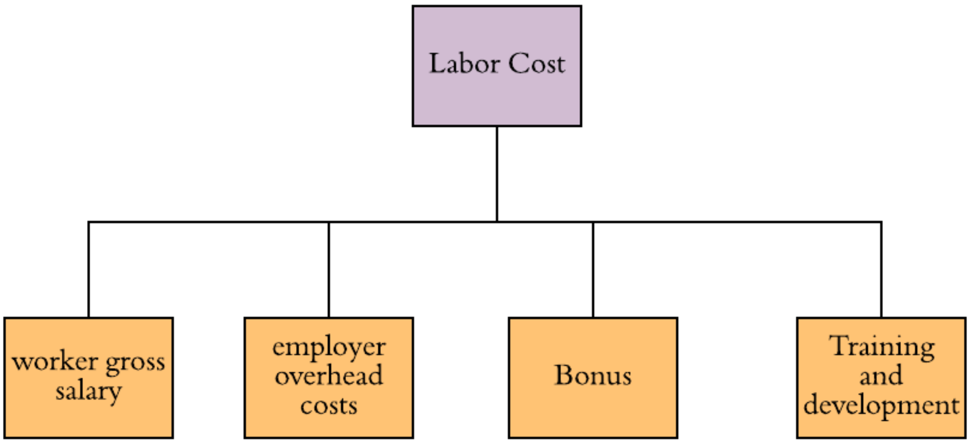


Figure 62: Labour cost model. Source: Own illustration.

The worker gross salary is the taxable salary paid by the company to the worker. As the facility is to be built in Germany, the salaries included in the calculation are based on the typical salaries in the German market. The direct labour considered in the cost calculation and the corresponding gross salary is shown in table 23.

Table 23: labour salaries and responsibilities

labour	number of workers	Gross salary	Responsibility
Assembly worker	4	3,000.00 €	Assembly station worker
Assembly logistics worker	1	3,000.00 €	The assembly line logistics
Foreman	1	4,500.00 €	EOL test station
warehouse logistics	1	3,000.00 €	Warehouse logistics
Supply chain	0.5	4,500.00 €	Managing assembly line supply chain (work capacity 50%)
Quality control	1	4,500.00 €	Quality control of finished goods and supplied parts
production planning	1	4,500.00 €	Production planning of assembly line

Employer overhead costs are the costs accompanying the employment of a worker. Insurances paid are social insurance, health insurance, unemployment insurance, pension insurance and accident insurance. Hiring costs are considered in the employer overhead costs and is calculated based on an interview with a cost expert at the partner company. Summarized employer overhead cost is shown below in table 24. [73]

Table 24: overhead calculation

Overhead	value
Health Insurance (7.2%)	7.20%
Pension insurance (9.3%)	9.30%
Unemployment insurance (1.25%)	1.25%
Nursing insurance (1.525%)	1.53%
Accident insurance (1.6%)	1.60%
Hiring cost/ worker	1,565.00 €
clothing/ worker	250.00 €

Bonus is the typical payment by the employer for the vacation and Christmas bonuses and calculated as following:

- Vacation bonus = $\frac{13 \text{ x gross salary per week}}{13 \text{ x working days per week}}$ x 10

- Christmas bonus = 55% x gross salary per month

The labour training and development was assumed 3% of the yearly gross salary for each worker / employee.

5.3. Machine costs

The machine cost is the cost of equipment, tools and technologies used to assemble the e-axle. The model below in figure 65 shows how the machine cost is calculated.

The model is split to three parts:

- Acquisition cost which is the cost related to acquire the machine in house as shipping cost, installation cost and purchase price

- Operation cost which is the cost related to the operation of machine itself as energy, wastes and tools

- Investment cost which is the cost related to the depreciation, the opportunity cost represented in bank interest and inflation represented in price index

[73] Jeitler (2019)

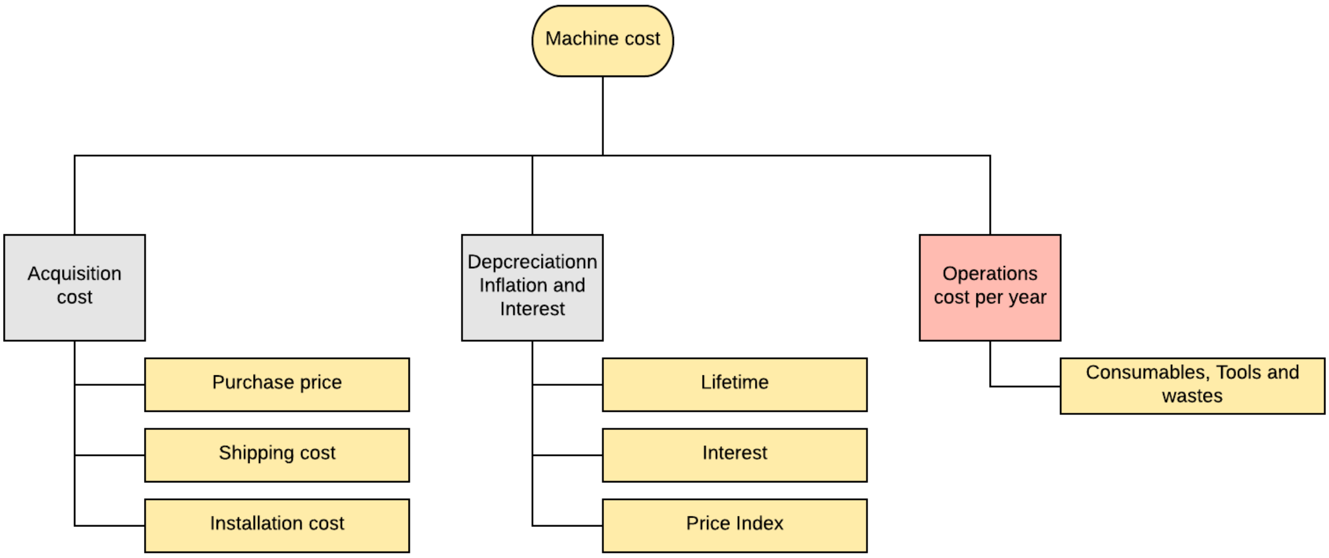


Figure 63: Machine cost model. Source: Own illustration.

The following assumptions were used throughout the machine costs calculation:

- Shipping cost is considered as a percentage of the purchase price and ranging from 1-5% based on the machine
- Installation cost is considered as a percentage of the purchase price and ranging from 1-5 % based on the machine
- The project is considered to be running for 3 years as requested by the partner company. The lifetime of the machines was assumed to be 3 years, and the reselling of the machine is not considered
- The interest is considered to be 8% and fixed over the 3 years
- The price index is calculated to be 110%
- The energy cost is not considered for each specific machine, but was assumed for the whole line based on an input from the partner company
- The tools, wastes and consumables cost are considered as a percentage of the purchase price and ranging from 1-3%
- The space cost is not considered for each specific machine but was calculated for the whole assembly line

The detailed machine cost calculation can be found in appendix J.

5.4. Development Cost

The development cost is the cost of developing and building the assembly line. The costs were provided by the partner company and can be summarized in table 25 below.

Table 25: Development cost

Cost centre	Cost
Project management	€ 262,500.00
Supplier Sourcing/ Audit	€ 350,000.00
process development and installation	€ 105,000.00
Product development and documentation	€ 120,000.00
Logistics Concepts	€ 35,000.00
Investment planning	€ 50,000.00
Incoming costs	€ 40,000.00
Misc.	€ 50,000.00

The following assumptions were used for calculating the development costs:

- Project lifetime is 3 years
- The interest rate used is 8%
- The price index is 110%

5.5. Overheads and profit margin

The overhead cost is the costs related to the administration, management, sales and marketing of product / assembly line. The overhead cost is calculated based on an interview with the cost expert at the partner company and is equal to 12%. [74]

The profit margin is the margin between the selling price and the total costs. Typically, in the automotive industry a profit margin of 7-8% is considered. This project is considered high risk in the automotive industry, a profit margin of 20% was requested from the partner company to be considered during the calculation.

5.6. Results

In this section, the cost results of the different scenarios presented in the simulation section will be discussed. The results of the cost model can be summarized in table 26 below.

[74] Jeitler (2019)

Table 26: total costs

Cost centre	Cost
Workstations	€ 82,451.25
Machines	€ 866,077.12
Warehouse and logistics	€ 37,727.79
Adaptive tools	€ 9,855.54
Maintenance (3.5%)	€ 34,863.91
Energy	€ 10,000.00
Space	€ 24,000.00
Development	€ 460,350.00
Insurance	€ 16,000.00
labour	€ 547,735.75
Material Direct e-axle D	€ 5,747.00
Material Direct e-axle L	€ 5,585.00
warehouse (1000 m^2)	€ 90,000.00
Scrap / e-axle D	€ 114.94
Scrap / e-axle L	€ 111.70

The insurance cost is calculated based on an input from the partner company and the maintenance cost is calculated based on 3.5% of the total machines' cost.

Based on the different scenarios simulated earlier, the different throughputs were calculated. The throughputs are used to calculate the e-axle cost for each scenario.

The adaptive concepts benefit was calculated as follows:

- The throughput was calculated without considering the adaptive concepts
- The throughput was calculated with considering each technology
- The e-axle price was calculated for both cases

Figure 64 below shows the different throughputs with implemented adaptive technologies.

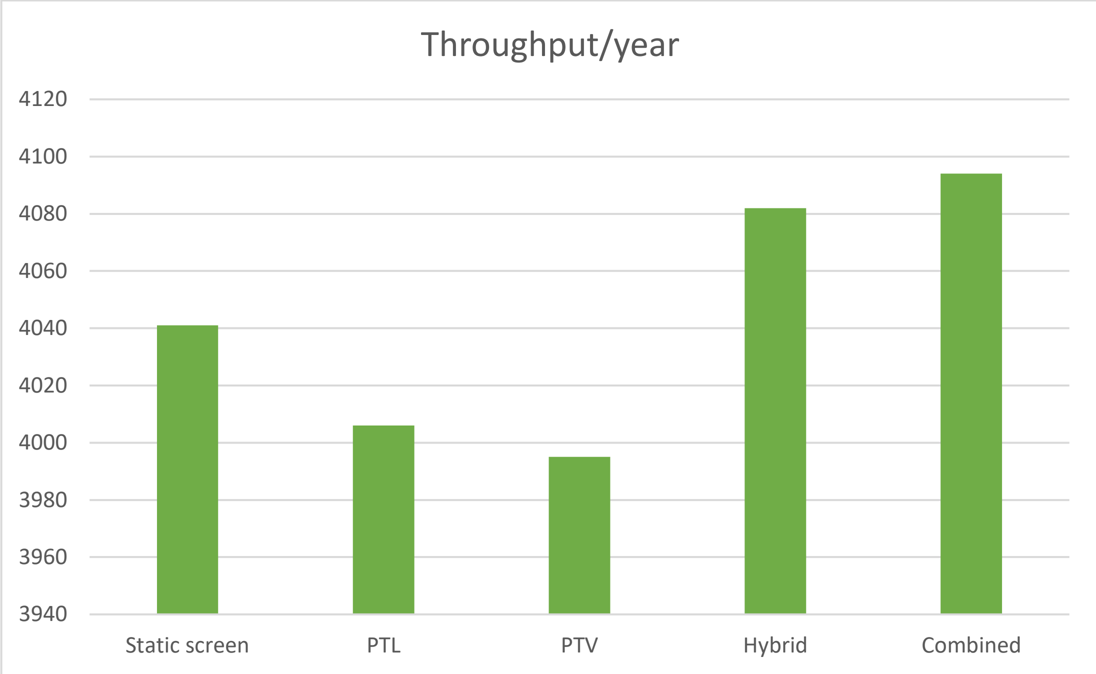


Figure 64: adaptive technologies throughput. Source: Own illustration.

Based on the throughputs the gain from each technology is calculated and shown in figure 65 below.

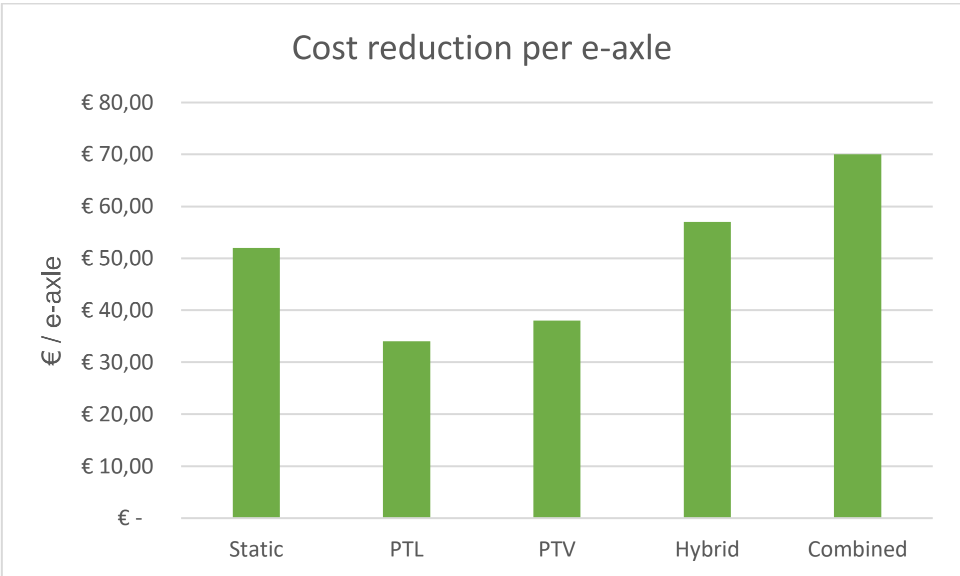


Figure 65: Cost reduction by adaptive technologies. Source: Own illustration.

The results showed that the maximum gain for the whole technologies together is 70 euros saved per e-axle, and the maximum gain from a technology is the hybrid system with 57 euros per e-axle.

The results of the simulation run of the different e-axles sequence performed in section 4.5 were used. The e-axle price for D and L are shown in figure 68.

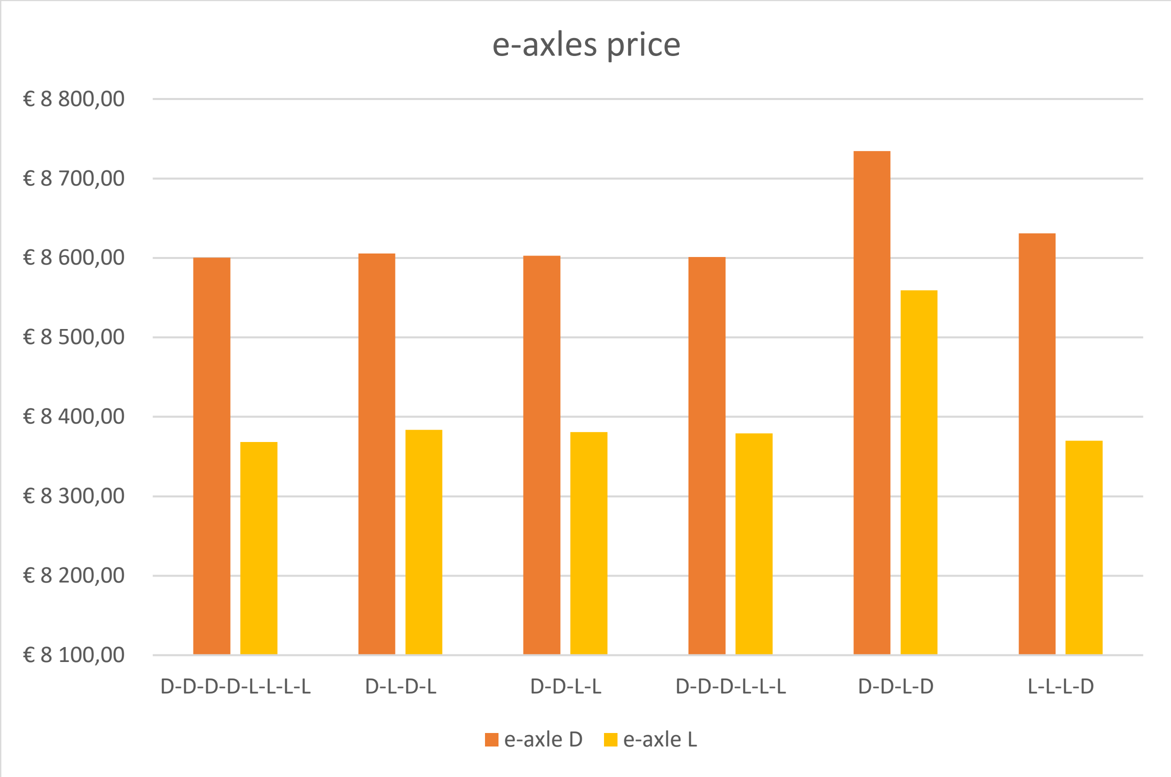


Figure 66: e-axle price. Source: Own illustration.

The e-axle prices from the graph show that the maximum price when 75% e-axle D and equals to 8734.26 € for e-axle D and 8559.18 € for e-axle L. The minimum price is when it is 50% e-axle D with four same e-axles in sequence with 8600 € for e-axle D and 8368 € for e-axle L.

Conclusion

Integrated e-axle is a growing configuration in the e-powertrain architecture, and study showed that there are different configurations for e-axles. Adaptive assembly line is a key enabling feature for assembling high variety products on the same assembly line with low rework percentage and limited reduction in productivity. The U-shaped assembly line showed adaptive benefits related to the demand variation as well as the assembly steps and balancing of the line. The different technologies investigated were shortlisted to the technologies with high readiness level as pick to light (PTL), static screen, pick to voice (PTV) and hybrid system of PTL and PTV. Simulation using Tecnomatix showed a high potential cost savings up to 54 euros per e-axle when the adaptive technologies are used. The simulation also showed increase in the annual throughput based on the introduction of the e-axles sequence to the assembly line.

The next step for this project is to validate the potential benefits of the adaptive concepts as well as the proposed layout. The technologies with medium readiness level need to be studied to evaluate the potential benefit for the assembly line if implemented in the next 5 years' period.

List of Tables

Table 1: Charging modes. Source: Policies (2018) 3
Table 2: Modified manufacturing system requirements. Source: Bangsow (2016). 27
Table 3: Qualitative rating scale 32
Table 4: Transmission and motor step 34
Table 5: Stator and Rotor step 34
Table 6: Shifting and Differential step 35
Table 7: Parking lock and Main step 35
Table 8: Closing and sealing step 35
Table 9: Process Machine table 36
Table 10: stations categorizing 37
Table 11: Severity transfer 42
Table 12: productivity example 43
Table 13: Rework transfer 43
Table 14: Tasks distribution 48
Table 15: Task distribution Initial layout 55
Table 16: steps distribution for the optimized layout 58
Table 17: Adaptive technologies effect 60
Table 18: station's increase in productivity 60
Table 19: Adaptive technologies throughput 61
Table 20: e-axles Sequence 61
Table 21: Direct material costs 64
Table 22: Indirect material costs 65
Table 23: labour salaries and responsibilities 65
Table 24: overhead calculation 66
Table 25: Development cost 68
Table 26: total costs 69

List of Figures

Figure 1: EV sales. Source: Policies (2018). 1

Figure 2: Barriers of electric vehicle. Source: Cecere (2018). 2

Figure 3: charging point density. Source: policies (2018) 4

Figure 4: Parallel Hybrid powertrain. Source: Yang et al. (2016). 5

Figure 5: Series Hybrid Powertrain. Source: Borthakur (2019). 6

Figure 6: PEV schematic. Source: Yang et al. (2016). 6

Figure 7: Integrated e-axle (a) assembled view. Source: Nissan online source on 28.10.2019 (2019). (b) components view. Source: Schermann (2015). 7

Figure 8: E-axles variants. Source: Own illustration. 9

Figure 9: Gear types. Source: KHK Gear (2006). 10

Figure 10: Different bearing types. Source: Bahandari (2016). 11

Figure 11: Extract preloading using spring. Source: NTN (2015). 13

Figure 12: Shifting mechanism. Source: Zhang et al. (2018). 13

Figure 13: Shifting by electric motor modified. Source: Zhang et al. (2018). 14

Figure 14: Natural passive cooling. Source: Gai et al. (2019). 14

Figure 15: Enclosed fan cooling. Source: Gai, et al. (2019). 15

Figure 16: Open fan cooling. Source: Gai et al. (2019). 15

Figure 17: Housing jacket tolerance effect. Source: Gai et al. (2019). 16

Figure 18: Stator cooling sleeve. Source: Gai et al. (2019). 16

Figure 19: Rotor cooling method. Source: Gai et al. (2019). 17

Figure 20: parking lock mechanism. Source: Mahale et al. (2007). 17

Figure 21: (a) Extract labyrinth configuration. Source: Khayal (2017), (b) radial shaft seal. Source: SKF (2014) 18

Figure 22: Adaptive technologies for e-axles. Source: Brillinger et al (2019). 19

Figure 23: Modified pick to light architecture. Source: Abdul Hadi (2019) 20

Figure 24: Pick to voice system. Source: rebstorage.com online source on 29.10.2019. 21

Figure 25: Picture instructions on screen. Source: Belusko et al. (2016). 21

Figure 26: Forklift AGV. Source: Ullrich (2015). 22

Figure 27: (a) Piggyback AGV (b) Assembly AGV. Source: Ullrich (2015). 22

Figure 28: Mini AGV. Source: Ullrich (2015). 23

Figure 29: Robotic Vision control. Source: Tingelstand et al. (2014). 23

Figure 30: different layouts. Source: Carlo et al. (2013). 24

Figure 31: Flow lines. Source: Kassir (2015). 25

Figure 32: Workers in U-shaped assembly. Source: Own illustration. 26

Figure 33: Simulation types. Source: Own illustration. 26
Figure 34: seven steps approach. Source: Law (2009). 29
Figure 35 Total cost of ownership model. Source: Rosenback (2013) 30
Figure 36: Modified TCO Framework. Source: Palkhi (2015). 31
Figure 37: Concept workflow. Source: Own illustration. 32
Figure 38: E-axle assembly overview. Source: Own illustration...33
Figure 39: Cobot. Source: Universal robots online source on 28.10.2019 37
Figure 40: U-shaped layout. Source: Own illustration. 39
Figure 41: Optimized U-shape assembly line. Source: Own illustration.................................39
Figure 42: Analysis steps. Source: Own illustration. 40
Figure 43: Productivity increase. Source: Own illustration 44
Figure 44: Rework reduction. Source: Own illustration 45
Figure 45: Simulation Workflow. Source: Own illustration 46
Figure 46: Partner company's Layout. Source: Rampe (2018). 47
Figure 47: Partner Company’s capacity analysis. Source: Rampe (2018). 49
Figure 48: Partner Company's layout simulation mainframe. Source: Own illustration. 50
Figure 49: pre-assembly frame. Source: Own illustration. 51
Figure 50: Station one Frame. Source: Own illustration. 52
Figure 51: station 2 Frame. Source: Own illustration...53
Figure 52: Initial Layout. Source: Own illustration. 54
Figure 53: Capacity analysis for initial layout. Source: Own illustration. 55
Figure 54: Assembly flow of e-axle L. Source: Own illustration. 56
Figure 55: capacity analysis for e-axles D and L. Source: Own illustration..............................57
Figure 56: Optimized layout. Source: Own illustration. 58
Figure 57: Capacity analysis for optimized layout. Source: Own illustration. 59
Figure 58: 3D schematic. Source: Own illustration. 59
Figure 59: different throughputs of sequence simulation runs. Source: Own illustration. 62
Figure 60: Cost model. Source: Own illustration. 63
Figure 61: Materials cost model. Source: Own illustration. 64
Figure 62: Labour cost model. Source: Own illustration. 65
Figure 63: Machine cost model. Source: Own illustration. 67
Figure 64: adaptive technologies throughput. Source: Own illustration. 70
Figure 65: Cost reduction by adaptive technologies. Source: Own illustration.........................70
Figure 66: e-axle price. Source: Own illustration...71

Appendix

Appendix A

Transmission	
Features	Rating
Helical single stage	1
Helical two stage	3
Planetary single stage	2
Planetary double stage	2
Multiple Gears (planets + helical)	1
Shifting	
Feature	Rating
Single speed	3
Double speed	1
Multiple speed (AMT)	1

Differential	
Feature	Rating
Conventional bevel gear Differential	3
Spur gear Differential	1
Helical gear Differential	1
Differential with superimposing	1
Limited Slip Differential (LSD)	1
Twin Clutch = torque vectoring	growing
Torque Vectoring	1
Disconnect system (Dog Clutch)	0

Feature	Rating
Natural passive cooling	0
Forced air (enclosed fan cooling)	0
Forced liquid (housing water jacket)	3
Forced liquid (stator cooling)	4
Forced liquid (Rotor cooling)	2

Appendix B

Occurrence Scale

Probability of Failure	Per Item Failure Rates	Ranking
Very High: Failure is almost inevitable	1 in 20	10
	1 in 30	9
High: Generally associated with processes similar to previous processes that have often failed	1 in 50	8
	1 in 80	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	1 in 120	6
	1 in 200	5
	1 in 500	4
Low: Isolated failures associated with similar processes	1 in 1000	3
Very Low: Only isolated failures associated with almost identical processes	1 in 1500	2
Remote: Failure is unlikely. No failures associated with almost identical processes	1 in 3000	1

Modified occurrence scale. Source: Abdul Hadi (2019).

Appendix C

Detection Scale

Detection	Criteria: Likelihood the existence of a defect will be detected by process controls before next or subsequent process, -OR- before exposure to a client	Ranking
Almost Impossible	No known controls available to detect failure mode	10
Very Remote	Very remote likelihood current controls will detect failure mode	9
Remote	Remote likelihood current controls will detect failure mode	8
Very Low	Very low likelihood current controls will detect failure mode	7
Low	Low likelihood current controls will detect failure mode	6
Moderate	Moderate likelihood current controls will detect failure mode	5
Moderately High	Moderately high likelihood current controls will detect failure mode	4
High	High likelihood current controls will detect failure mode	3
Very High	Very high likelihood current controls will detect failure mode	2
Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1

Detection scale. Source: Abdul Hadi (2019).

Appendix D

Severity Scale

Adapt as appropriate

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur **without** warning	10
Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur **with** warning	9
Very High	Major disruption of service involving client interaction, resulting in either associate re-work or inconvenience to client	8
High	Minor disruption of service involving client interaction and resulting in either associate re-work or inconvenience to clients	7
Moderate	Major disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	6
Low	Minor disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	5
Very Low	Minor disruption of service involving client interaction that does not result in either associate re-work or inconvenience to clients	4
Minor	Minor disruption of service not involving client interaction and does not result in either associate re-work or inconvenience to clients	3
Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associate re-work or inconvenience to clients	2
None	No Effect	1

Severity scale. Source: Abdul Hadi (2019).

Appendix E

Product	Most frequent process					
	process 1	Process 2	Process 3	Process 4	Process 5	process 6
Bearing	Interference fit by pressing of inner Race/ Induction Heating of shaft	Securing inner race with a snap ring	Interference by pressing of outer race/ Induction heating of Housing	Securing outer race with a snapring		
Sealant	Interference fit by pressing over the shaft	Interference fit by pressing with the Housing				
Shaft	Fixing over the fixture					
Gear	Transition fit over the shaft shoulder manually	Securing with a snap ring				
Synchronizer	Clearance fit for the Hub	Secure with a snapring	clearance fit for the Sleeve	2x Clearance fit for blocking ring		
Shifting actuator	Clearance fit for the actuator to Housing	Fixing the Actuation by bolt	Clearance fit shifting fork	Fixing fork by bolts		
Differential	Clearance fit differential over the ring gear	Fixing the differential to ring gear by bolts	Interference by pressing of inner race over differential	Interference by pressing Outer Race in Housing	Interference by Pressing differential to Housing	

Planet Gear	Interference by pressing bearing to Gear	2x Clearance fit for washer	Interference fit for Gear shaft	Secure with Snapring/spacer ring/axial washer		
Cooling system	2x Clearance fit water jacket to EM cover	2x fix water jacket to EM cover by bolts	Assemble coolant lines			
Electric motor	Interference fit Stator components by pressing/Induction heating	Bearing to rotor and housing	assemble cooling system	Clearance fit EM to Housing	Fix by bolts to Housing	
Oiling system (small parts)	Assembly in housing	Bolting in housing				
Cover	Clearance fit cover to Housing	Fix cover to Housing by bolts				
Clutch	3x Transition fit of the Friction desk to shaft	3x Clearance fit of the steel plate to shaft	Clearance fit Clutch Housing to main Housing	Fixing Clutch Housing by bolts		
Parking Lock	clearance fit Bracket with fork to housing	Fix the bracket to housing	transition fit actuator rod to fork and bracket	Transition fit spring and pawl to shaft	Clearance fit actuator to housing	Fix Actuator to housing and to fork
Electronics	Assemble	Bolting				
Sun Gear	Interference fit Bearing to shaft by pressing	Interference fit bearing by pressing with the Housing	Transition fit spline to input shaft	Transition fit to planetary gear carrier	Secure with Snapring/spacer ring/axial washer	Interference fit Sealing washer

Planet carrier	Interference fit Bearing to planet carrier	Interference fit bearing with Housing				
Ring Gear	Clearance fit to Housing/Input gear	Fix by bolts to Housing				

Feature	**Components**								
	Gear	Bearing	Shaft	Electric motor	Clutch	Sealant	synchronizer	shifting actuation	Differential
single stage single speed	2	4	2	N/A	N/A	2	N/A	N/A	N/A
single stage two speeds	2	4	2	1	N/A	2	1	1	N/A
Double stage single stage	4	6	3	N/A	N/A	2	N/A	N/A	N/A
Double stage two speeds	4	6	3	N/A	N/A	2	1	1	N/A
Double stage multiple(n) speeds	4+(n-2) *2	6	3	N/A	N/A	2	(n-1)	(n-1)	N/A
Single Planetary	N/A	4	1	0	N/A	2	N/A	N/A	N/A
Double stage Planetary	N/A	6	1	N/A	N/A	2	N/A	N/A	N/A
Planetary-Helical Gearing	2	6	2	N/A	N/A	2	N/A	N/A	N/A
Single Motor	N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	1
Double Motor	N/A	N/A	N/A	2	N/A	N/A	N/A	N/A	0
Bevel Differential with superimposing unit	6	4	2	N/A	2	N/A	N/A	N/A	1
Twin Clutch	N/A	N/A	1	N/A	2	N/A	N/A	N/A	0

Feature	Components			
	Special component 1	Special Component 2	Special Component 3	Special component 4
single stage single speed				
single stage two speeds				
Double stage single stage				
Double stage two speeds				
Double stage multiple(n) speeds				
Single Planetary	3x Planet Gear	1 x Sun Gear	Planet carrier	Cover (special)
Double stage Planetary	6x planet Gear	2 x sun Gear	2x Planet Carrier	2x Cover (special)
Planetary-Helical Gearing	3x Planet Gear	1 x Sun Gear	Planet Carrier	Cover (special)
Single Motor				Cover
Double Motor				2 x Cover
Bevel Differential with superimposing unit	2xRing Gear			
Twin Clutch	Ring Gear			

Appendix F

Productivity rating

Category	Potential failure mode	potential effects	severity	Potential causes	Occurrence	Current control	Detection	RPN
Person related	Poor skill level	Quality which leads to failure of e-axle	8	Due to inadequate skill training (low qualification of worker)	6	None	***8***	***384***
Information	Poor or missing documentation - Process description	Incorrect assemblies or incorrect parts used	10	Huge rework and additional times that causes unknown expenses	8	Verbal notification by the workers	***8***	***640***
Person related	Wrong judgement of the shown description while assembly	Can lead to any type of assembly errors	5	Impatient operation by worker	5	Experienced workforce	***8***	***200***
Assistive operation	Wrong tools, parts	Leads to higher utilization or efforts by the worker	7	Increase in assembly times	6	Monitoring by respective station workers	***4***	***168***

Person related	Planning and controlling errors	Increase in takt times and lower output volume	8	Due to poor schedule, or time allocation for tasks	9	More time allocation for next batch	***8***	***576***
other	Unexpected events	Halt in the assembly process, quality issues	9	Can be related to improper description of tasks, etc.	7	None. Worker gets experienced over a period	***6***	***378***
Assistive operation	Missing of immediate guidance	quality issues, lower throughput	9	Increase in assembly times	7	None. Worker gets experienced over a period	***4***	***252***
Assistive operation	Searching for parts and tools	lower throughput	6	Increase in assembly times	10	None, more time allocation	***4***	***240***

Modified FMEA. Source: Abdul Hadi (2019).

	Original			Static screen		Pick to Light		Pick to voice	
Category	Potential failure mode	severity	Occurrence	Severity	Occurrence	Severity	Occurrence	Severity	Occurrence
Person related	Poor skill level	8	6	7	4	7	6	6	4
Information	Poor or missing documentation - Process description	10	8	9	5	10	7	8	8
Person related	Wrong judgement of the shown description while assembly	5	5	5	4	3	5	4	5
Assistive operation	Wrong tools, parts	7	6	7	5	6	2	7	5
Person related	Planning and controlling errors	8	9	8	8	8	9	7	8
other	Unexpected events	9	7	9	7	9	7	7	7
Assistive operation	Missing of immediate guidance	9	7	9	6	9	6	6	7
Assistive operation	Searching for parts and tools	6	10	5	9	3	5	5	9

Original				Hybrid system		Combined	
Category	Potential failure mode	severity	Occurrence	Severity	Occurrence	Severity	Occurrence
Person related	Poor skill level	8	6	6	4	6	4
Information	Poor or missing documentation - Process description	10	8	8	8	9	5
Person related	Wrong judgement of the shown description while assembly	5	5	3	4	3	4
Assistive operation	Wrong tools, parts	7	6	5	2	5	2
Person related	Planning and controlling errors	8	9	7	8	7	8
other	Unexpected events	9	7	7	7	7	7
Assistive operation	Missing of immediate guidance	9	7	5	6	5	6
Assistive operation	Searching for parts and tools	6	10	2	5	2	5

Appendix G
Rework rating

Category	Potential failure mode	Potential effects	Severity	Potential causes	Occurrence	Current control	Detection	RPN
Person related	Poor skill level	Quality which leads to failure of e-axle	9	Due to inadequate skill training (low qualification of worker)	6	None	***8***	*432*
Information	Poor or missing documentation - Process description	Incorrect assemblies or incorrect parts used	8	Time pressure, High number of products	8	Verbal notification by the workers	***8***	*512*
Person related	Wrong judgement of the shown description while assembly	Can lead to any type of assembly errors	8	Impatient operation by worker	5	Experienced workforce	***8***	*320*
Person related	Negligence errors due to fatigue or psychological stress (tired and mental stress)	Quality which leads to failure of e-axle	6	Due to fatigue (tiredness) or psychological stress	5	None	3	*90*

Assistive operation	Lack of prevention measures	Injuries or unexpected errors	4	No fixed monitoring techniques	4	Visual inspection and notification given verbally by workers	8	*128*
Assistive operation	Wrong tools, broken tools, parts	Leads to higher utilization or efforts by the worker, ruin parts	8	Time pressure, High number of products	6	Monitoring by respective station workers	***4***	*192*
Audit	Error in quality inspection	Quality related errors which can be detected at final stages and require huge rework or detected by the customer	9	No fixed inspection methods	7	None	6	*378*
other	Unexpected events	Halt in the assembly process, quality issues	8	Can be related to improper description of tasks, etc.	7	None. Worker gets experienced over a period	***6***	*336*

Modified FMEA. Source: Abdul Hadi (2019).

Original					Static Screen	PTL	PTV
Category	Potential failure mode	Severity	Occurrence	Detection	Occurrence	Occurrence	Occurrence
Person related	Poor skill level	9	6	***8***	4	6	4
Information	Poor or missing documentation - Process description	8	8	***8***	5	7	8
Person related	Wrong judgement of the shown description while assembly	8	5	***8***	4	5	5
Person related	Negligence errors due to fatigue or psychological stress (tired and mental stress)	6	5	3	5	5	4
Assistive operation	Lack of prevention measures	4	4	8	3	3	3
Assistive operation	Wrong tools, broken tools, parts	8	6	***4***	5	2	5

Audit	Error in quality inspection	9	7	6	5	7	6
other	Unexpected events	8	7	***6***	7	7	7

Original					Hybrid system	Combined technologies
Category	Potential failure mode	Severity	Occurrence	Detection	Occurrence	Occurrence
Person related	Poor skill level	9	6	**8**	4	4
Information	Poor or missing documentation - Process description	8	8	**8**	7	5
Person related	Wrong judgement of the shown description while assembly	8	5	**8**	4	4
Person related	Negligence errors due to fatigue or psychological stress (tired and mental stress)	6	5	6	4	4
Assistive operation	Lack of prevention measures	4	4	8	3	3

Assistive operation	Wrong tools, broken tools, parts	8	6	**4**	2	2
Audit	Error in quality inspection	9	7		6	5
other	Unexpected events	8	7	**6**	7	7

Appendix H

Monthly wage	Assembly worker	Assembly logistics worker	Foreman	warehouse logistics	Supply chain	Quality control	production planning
Gross salary	3,000.00 €	3,000.00 €	4,500.00 €	3,000.00 €	4,500.00 €	4,500.00 €	4,500.00 €
Health Insurance (7.2%)	216.00 €	216.00 €	324.00 €	216.00 €	324.00 €	324.00 €	324.00 €
Pension insurance (9.3%)	279.00 €	279.00 €	418.50 €	279.00 €	418.50 €	418.50 €	418.50 €
Unemployment insurance (1.25%)	37.50 €	37.50 €	56.25 €	37.50 €	56.25 €	56.25 €	56.25 €
Nursing insurance (1.525%)	37.50 €	37.50 €	56.25 €	37.50 €	56.25 €	56.25 €	56.25 €
Accident insurance (1.6%)	48.00 €	48.00 €	72.00 €	48.00 €	72.00 €	72.00 €	72.00 €
Total Gross Salary	3,618.00 €	3,618.00 €	5,427.00 €	3,618.00 €	5,427.00 €	5,427.00 €	5,427.00 €

Bonus	Assembly worker	Assembly logistics worker	Foreman	warehouse logistics	Supply chain	Quality control	production planning
Vacation Bonus	1,500.00 €	1,500.00 €	2,250.00 €	1,500.00 €	2,250.00 €	2,250.00 €	2,250.00 €
Christmas Bonus(55%)	1,650.00 €	1,650.00 €	2,475.00 €	1,650.00 €	2,475.00 €	2,475.00 €	2,475.00 €
Total Bonus	3,150.00 €	3,150.00 €	4,725.00 €	3,150.00 €	4,725.00 €	4,725.00 €	4,725.00 €

Additional costs	Assembly worker	Assembly logistics worker	Foreman	warehouse logistics	Supply chain	Quality control	production planning
Hiring costs (average 3 years)	1,565.00 €	1,565.00 €	1,565.00 €	1,565.00 €	1,565.00 €	1,565.00 €	1,565.00 €
Training and development (3%)	1,396.98 €	1,396.98 €	2,095.47 €	1,396.98 €	2,095.47 €	2,095.47 €	2,095.47 €
Clothes	250.00 €	250.00 €	250.00 €	250.00 €	- €	100.00 €	- €
Total Additional costs	3,211.98 €	3,211.98 €	3,910.47 €	3,211.98 €	3,660.47 €	3,760.47 €	3,660.47 €

Total	Assembly worker	Assembly logistics worker	Foreman	warehouse logistics	Supply chain	Quality control	production planning
Total Gross salary/year	€ 47,636.66	€ 49,777.98	€ 73,759.47	€ 49,777.98	€ 73,509.47	€ 73,609.47	€ 73,509.47
Number of workers	4	1	1	1	0.5	1	1
Total salary	€ 190,546.64	€ 49,777.98	€ 73,759.47	€ 49,777.98	€ 36,754.74	€ 73,609.47	€ 73,509.47
Total							547,735.75 €

Cost center	cost
Labor	€ 547,735.75
Throughput	4167
Labor cost/axle	€ 131.45

Appendix I

Working stations	Quantit	Purchase price	Installation cost	Shipping Costs	Acquisition Cost	Price Index (110%	Interest (8%)	Lifetime (3 yea	Depreciation/year per i	Total Depreciation / Year
Table Frame	4	€ 654.00	€ 13.08	€ 19.62	€ 686.70	€ 755.37	€ 60.43	3	€ 312.22	€ 1,248.88
Top Assembly plate	4	€ 356.00	€ 7.12	€ 10.68	€ 373.80	€ 411.18	€ 32.89	3	€ 169.95	€ 679.82
Tool Holder set	4	€ 119.00	€ 2.38	€ 3.57	€ 124.95	€ 137.45	€ 11.00	3	€ 56.81	€ 227.24
Clamping tool	4	€ 34.00	€ 0.68	€ 1.02	€ 35.70	€ 39.27	€ 3.14	3	€ 16.23	€ 64.93
roller	4	€ 128.00	€ 2.56	€ 3.84	€ 134.40	€ 147.84	€ 11.83	3	€ 61.11	€ 244.43
Compressed air connecti	4	€ 57.00	€ 1.14	€ 1.71	€ 59.85	€ 65.84	€ 5.27	3	€ 27.21	€ 108.85
ESD footrest	4	€ 115.00	€ 2.30	€ 3.45	€ 120.75	€ 132.83	€ 10.63	3	€ 54.90	€ 219.60
Tool kit	4	€ 225.00	€ 4.50	€ 6.75	€ 236.25	€ 259.88	€ 20.79	3	€ 107.42	€ 429.66
Screenholder	4	€ 206.00	€ 4.12	€ 6.18	€ 216.30	€ 237.93	€ 19.03	3	€ 98.34	€ 393.38
Screen	4	€ 129.00	€ 2.58	€ 3.87	€ 135.45	€ 149.00	€ 11.92	3	€ 61.58	€ 246.34
Working chair	4	€ 350.00	€ 7.00	€ 10.50	€ 367.50	€ 404.25	€ 32.34	3	€ 167.09	€ 668.36
Discharge element	4	€ 685.00	€ 13.70	€ 20.55	€ 719.25	€ 791.18	€ 63.29	3	€ 327.02	€ 1,308.08
Workpiece carrier	16	€ 70.00	€ 1.40	€ 2.10	€ 73.50	€ 80.85	€ 6.47	3	€ 33.42	€ 534.69
Mounting device	16	€ 9,000.00	€ 180.00	€ 270.00	€ 9,450.00	€ 10,395.00	€ 831.60	3	€ 4,296.60	€ 68,745.60
Trolley	8	€ 1,050.00	€ 21.00	€ 31.50	€ 1,102.50	€ 1,212.75	€ 97.02	3	€ 501.27	€ 4,010.16
Positioning aid kit	4	€ 181.00	€ 3.62	€ 5.43	€ 190.05	€ 209.06	€ 16.72	3	€ 86.41	€ 345.64
Base frame	4	€ 724.00	€ 14.48	€ 21.72	€ 760.20	€ 836.22	€ 66.90	3	€ 345.64	€ 1,382.55
FIFO	4	€ 191.00	€ 3.82	€ 5.73	€ 200.55	€ 220.61	€ 17.65	3	€ 91.18	€ 364.73
Dividers	4	€ 63.00	€ 1.26	€ 1.89	€ 66.15	€ 72.77	€ 5.82	3	€ 30.08	€ 120.30
Rollers	4	€ 181.00	€ 3.62	€ 5.43	€ 190.05	€ 209.06	€ 16.72	3	€ 86.41	€ 345.64
Containers Size 2	64	€ 3.00	€ 2.50	€ 0.30	€ 5.80	€ 6.38	€ 0.51	3	€ 2.64	€ 168.77
Containers Size 5	36	€ 5.00	€ 2.50	€ 0.50	€ 8.00	€ 8.80	€ 0.70	3	€ 3.64	€ 130.94
Containers 60*40	48	€ 17.00	€ 2.50	€ 1.70	€ 21.20	€ 23.32	€ 1.87	3	€ 9.64	€ 462.67
					Total					€ 82,451.25

Appendix J

Machines and tools	Quantity	purchasing price	Installation cost (5%)	Shipping Costs (4%)	Total Acquisition price	Price Index (110%)	Interest (8%)
Line unit (1m)	13	€ 753.00	€ 37.65	€ 30.12	€ 820.77	€ 902.85	€ 72.23
Angle wrench	6	€ 6,250.00	€ -	€ 250.00	€ 6,500.00	€ 7,150.00	€ 572.00
charging craddle	6	€ 1,020.00	€ 51.00	€ 40.80	€ 1,111.80	€ 1,222.98	€ 97.84
Wrench	6	€ 100.00	€ -	€ 4.00	€ 104.00	€ 114.40	€ 9.15
Firmware PRW	6	€ 302.00	€ 15.10	€ 12.08	€ 329.18	€ 362.10	€ 28.97
Radio station	6	€ 800.00	€ 40.00	€ 32.00	€ 872.00	€ 959.20	€ 76.74
Software	1	€ 2,500.00	€ 125.00	€ 100.00	€ 2,725.00	€ 2,997.50	€ 239.80
Scanner	5	€ 610.00	€ 18.30	€ 18.30	€ 646.60	€ 711.26	€ 56.90
Collet	3	€ 20.00	€ 1.00	€ 0.80	€ 21.80	€ 23.98	€ 1.92
Delta robot	1	€ 15,000.00	€ 750.00	€ 600.00	€ 16,350.00	€ 17,985.00	€ 1,438.80
Automatic sealant	1	€ 15,000.00	€ 750.00	€ 600.00	€ 16,350.00	€ 17,985.00	€ 1,438.80
Induction Furance	2	€ 22,430.00	€ 1,121.50	€ 897.20	€ 24,448.70	€ 26,893.57	€ 2,151.49
Hydraulic press	2	€ 18,516.00	€ 925.80	€ 740.64	€ 20,182.44	€ 22,200.68	€ 1,776.05
Computer	6	€ 1,330.00	€ 66.50	€ 53.20	€ 1,449.70	€ 1,594.67	€ 127.57
Function test	1	€ 100,000.00	€ 5,000.00	€ 4,000.00	€ 109,000.00	€ 119,900.00	€ 9,592.00
Centering device	2	€ 5,000.00	€ 250.00	€ 200.00	€ 5,450.00	€ 5,995.00	€ 479.60
Insertion device for final assembly	1	€ 5,000.00	€ 250.00	€ 200.00	€ 5,450.00	€ 5,995.00	€ 479.60
EOL 1	1	€ 30,877.00	€ 1,543.85	€ 1,235.08	€ 33,655.93	€ 37,021.52	€ 2,961.72
EOL 2	1	€ 1,500,000.00	€ 30,000.00	€ 15,000.00	€ 1,545,000.00	€ 1,699,500.00	€ 135,960.00
						Total	

Appendix K

Machines and tools	Quantity	Purchasing price/item	Installation cost (1-3%)	Shipping Costs (3-5%)	Total Acquisition price
Pallets (EUR)	16	€ 75.00	€ 1.50	€ 2.25	€ 78.75
Finished good box	20	€ 339.00	€ 6.78	€ 10.17	€ 355.95
Forklift	2	€ 25,000.00	€ 250.00	€ 1,250.00	€ 26,500.00
Crane	1	€ 20,000.00	€ 600.00	€ 1,000.00	€ 21,600.00

Machines and tools	Price Index (110%)	Interest (8%)	Lifetime (3 years)	Depreciation/year per item	Total Depreciation / Year	Consumables and wastes (1-3%)	Total
Pallets (EUR)	€ 86.63	€ 6.93	3	€ 35.81	€ 572.88	€ 0.75	€ 573.63
Finished good box	€ 391.55	€ 31.32	3	€ 161.84	€ 3,236.77	€ 3.39	€ 3,240.16
Forklift	€ 29,150.00	€ 2,332.00	3	€ 12,048.67	€ 24,097.33	€ 750.00	€ 24,847.33
Crane	€ 23,760.00	€ 1,900.80	3	€ 9,820.80	€ 9,820.80	€ 0.03	€ 9,820.83
Total							37,727.79 €

Appendix L

Cost center	Cost	Price index (110%)	Interest (8%)	System lifetime	Development per year
Project management	€ 262,500.00	€ 288,750.00	€ 23,100.00	3	€ 119,350.00
Supplier Sourcing/ Audit	€ 350,000.00	€ 385,000.00	€ 30,800.00	3	€ 159,133.33
process development and installation	€ 105,000.00	€ 115,500.00	€ 9,240.00	3	€ 47,740.00
Product development and documentation	€ 120,000.00	€ 132,000.00	€ 10,560.00	3	€ 54,560.00
Logistics Concepts	€ 35,000.00	€ 38,500.00	€ 3,080.00	3	€ 15,913.33
Investment planning	€ 50,000.00	€ 55,000.00	€ 4,400.00	3	€ 22,733.33
Incoming costs	€ 40,000.00	€ 44,000.00	€ 3,520.00	3	€ 18,186.67
Misc	€ 50,000.00	€ 55,000.00	€ 4,400.00	3	€ 22,733.33
Total					€ 460,350.00

Cost center	Cost
Workstations	€ 82,451.25
Machines	€ 866,077.12
Warehouse and logstics	€ 37,727.79
Adaptive tools	€ 9,855.54
Maintenance (3.5%)	€ 34,863.91
Energy	€ 10,000.00
Space	€ 24,000.00
Development	€ 460,350.00
Insurance	€ 16,000.00
Total	€ 1,541,325.61
Throughput total	4167
Cost/Axle	€ 369.89

Appendix M

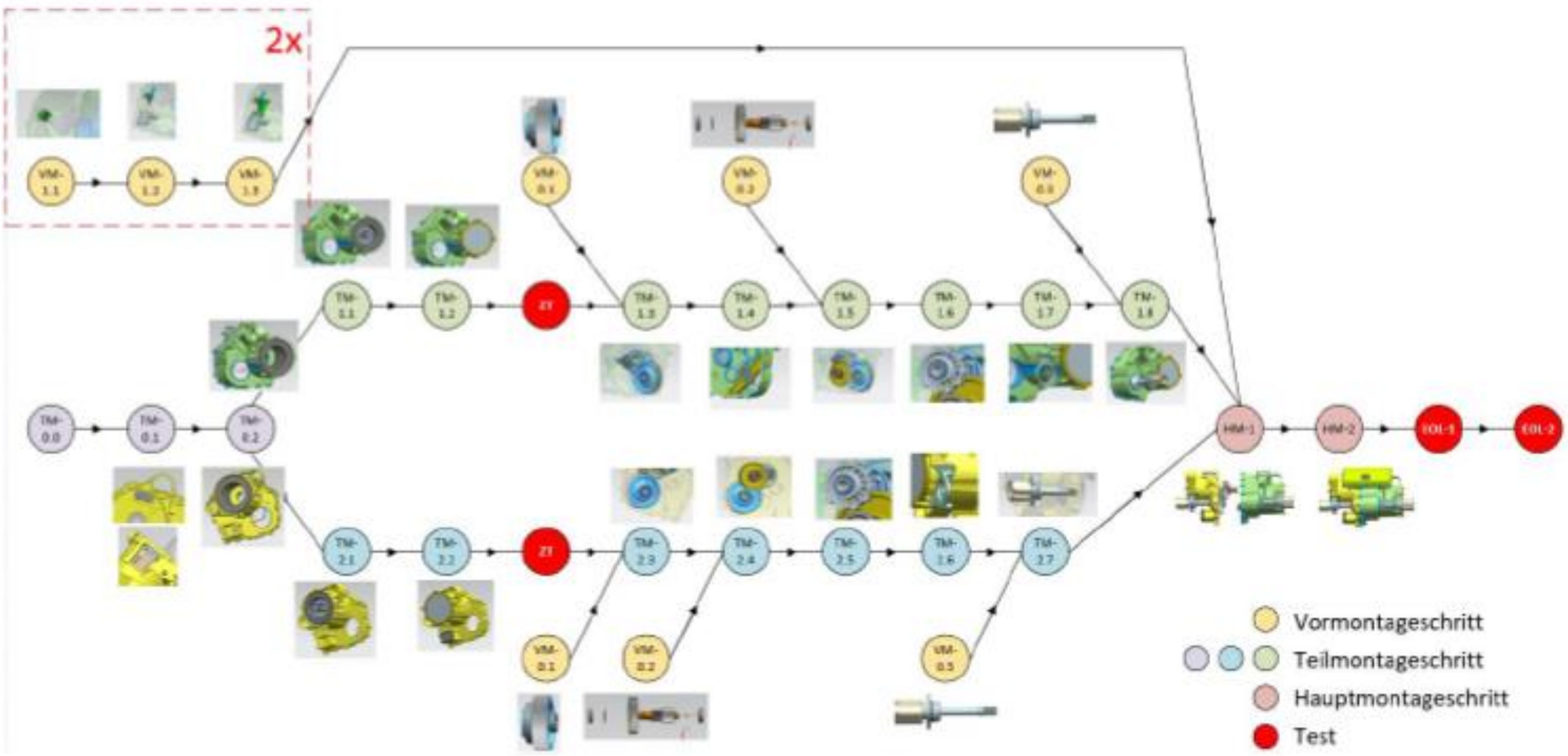
Station	ssembly Resourc	Assumptions		Total PTL
station	. Two FIFO . Table 120 cm	. FIFO no. of layers is 4 . FIFO 3 boxes / layer . Table has 3 layers . No. of Size 2 boxes per layer 8 . No. of Size 5 boxes per layer 5 . 2 layers of Size 2, 1 layer Size 5		45 Per Station
PTL Cost				
Device	**Cost**	**Assumption**		**Total**
PTL label	10.00 €	based on a label developed to Bossard which has nearly same function		1,800.00 €
Access point	125.00 €	Based on Access points sold by SES		250.00 €
WES	6,750.00 €	on store management software sold/ store		6,750.00 €
Total				8,800.00 €
Ear Device cost				
Device	**Cost**	**Assumption**		**Total**
Ear Device	450.00 €	based on amazon price of belt worn ear device		450.00 €
Installation and Configuration				
Cost of Initial installation	1,440.00 €	Based on an estimation of 3 days work to make the PTL go to live, with a 60 euros /HR		1,440.00 €

Appendix N

Machines and tools	Quantity	Purchasing price/item	Installation	Shipping Costs (2-3%)	Total Acquisition price	Price Index (110%)	Interest (8%)
PTL labels	180	€ 10.00	€ 1,440.00	€ 0.20	€ 10.20	€ 11.22	€ 0.90
Access points	2	€ 125.00		€ 3.75	€ 128.75	€ 141.63	€ 11.33
WES	1	€ 6,750.00		€ -	€ 6,750.00	€ 6,750.00	€ 540.00
Ear Device	5	€ 450.00		€ 9.00	€ 459.00	€ 504.90	€ 40.39
					Total system		

Machines and tools	Lifetime (3 years)	Depreciation/year per item	Total Depreciation / Year
PTL labels	3	€ 4.64	€ 834.77
Access points	3	€ 58.54	€ 117.08
WES	1	€ 7,290.00	€ 7,290.00
Ear Device	3	€ 208.69	€ 1,043.46
Total system			9,855.54 €

Appendix O



Source: Rampe (2018)

Appendix P

Nr.	Assembly Step ID	Summary	Description	steps	times
1	TM-0.0	Fasten on mounting device	Mount the housing half on the mounting device using 4 screws.	1	192
2	TM-0.1	Pre-assembly adapters eMOT & Inverter	To pre-install the adapter from inverter to eMOT, the lower part is first inserted into the housing of the stator, then the inverter side half attached and finally screwed both	1	184
3	TM-0.2	Pre-assembly Stator	ACCEPTANCE: "Stator is Poka Yoke designed" Warm up the housing Insert the stator Check connector adapter & stator	1	956
4	TM-1.1	Assembly eMOT_Rotor (incl. Bearing plate)	Connect rotor with centring device Warming shaft bearing on the housing side, Insert rotor Press in end shield in housing Dismantling centring device of the rotor	2	505
5	TM-1.2	Assembly cover eMOT	Warm up Storage of the rotor shaft Add end shield & cover Press on rotor shaft Screw on cover to housing	2	107
6	TM-1.3	Assembly Worm	Warming up bearings in the housing, Insert worm wheel, Look up with a hammer (check seat)	5	144
7	TM-1.4	Assembly counter shell	Warm up the bearing shell positioning Look up with mounting aid (check seat) screw on	6	176
8	TM-1.5	Assembly intermediate shaft	Warm up the bearing on the housing side insert intermediate shaft	7	137
9	TM-1.6	Assembly ParkingLock_Wheel	Plug PL_Wheel Secure with circlip Heat ball bearing inner ring Attach ball bearing	8	164

10	TM-1.7	Assembly outer bearing drive shaft	ACCEPTANCE: 2 screws, 2 dowel pins Stop bearing Turn in dowel pins Screw on screws	9	84
11	TM-1.8	Assembly drive shaft	Stopping the sealing pipe, Insert drive shaft Screw drive shaft	10	117
12	TM-2.1	Mounting eMOT_Rotor (incl. Bearing plate)	Connect rotor with centring device Warming shaft bearing on the housing side, Insert rotor Dismantling centring device of the rotor	2	505
13	TM-2.2	Mounting end shield, cover eMOT & charging socket	Warm up Storage of the rotor shaft Add end shield & cover Press on rotor shaft Screw on cover to housing Add charging socket Screw on charging socket	2	119
14	TM-2.3	Mounting worm wheel	Warming up bearings in the housing, Insert worm wheel, Look up with a hammer (check seat)	5	144
15	TM-2.4	Assembly intermediate shaft	Warm up the bearing on the housing side insert intermediate shaft	7	137
16	TM-2.5	Assembly ParkingLock_Wheel	Plug PL_Wheel Secure with circlip Heat ball bearing inner ring Attach ball bearing	8	164
17	TM-2.6	Mounting outer bearing drive shaft	ACCEPTANCE: 2 screws, 2 dowel pins Stop bearing Turn in dowel pins Screw on screws	9	84
18	TM-2.7	Assembly drive shaft	Stopping the sealing pipe, Insert drive shaft Screw drive shaft	10	117
19	VM-1.1	Guidance Parking Lock	Stopping guide cone Inserting dowel pins Attaching circlips	11	174
20	VM-1.2	Parking Lock drive	Plugging in the drive, Attaching the spring, Slipping the pin Screwing the pin	11	190

21	VM-1.3	pawl	Stopping latch, Plug in pin, Fasten the dowel pin with circlip on both sides, Attaching strut, Secure strut with circlip	11	228
22	VM-0.1	Pre-assembly worm wheel	induction heating of the bearings then put it on	4	250
23	VM-0.2	Pre-assembly of intermediate shaft	induction heating of the bearings, Putting on gear, secure the gear with locking ring, attach the bearings	7.1	312
24	VM-0.3	Pre-assembly drive shaft	Warming up the flange bearings, Slipping the flange bearings	10.1	252
25	HM-1	Assembly housing	Attach the mounting aid Apply sealing compound / sealing foil (internal bearings pointwise heating) Prevent Parking Lock (open) Put screwing together	12	930
26	HM-2	Inverter Attach	Electronics connect Connect coolant circuit Inverter positioning and alignment Screw inverter on	13	176
27	ZT	between test	Examination of the eMOT on function - Approach main operating point - Record the speed-torque characteristic	3	720
28	EOL-1	Leak Test	Checking the tightness - Tightness requirement IP 6K9K, IP 68 Filling with test oil	14	900
29	EOL-2	Function Test	End-of-line test - drag torque - Short circuit test - Speed torque characteristic - Gear play - full load test - Degree of utilization - NHV measurements (noise, vibration, roughness)	15	1440

Appendix Q

Nr	**Part**	Quantity	Description	Time
			Pre-Assembly outer housing	
P1	Transmission housing out L/R	1	Place housing <P1> in hydraulic press <TL1>	9
P2	Ring gear L/R	1	Clean housing <P1> with cleaning equipment <TL3>	4
P3	Deep grove ball bearing with groove	1	Place ring gear <P2> into housing <P1>	4
P4	Snap ring	1	Press in ring gear <P2> into housing <P1> with hydraulic press <TL1>	11
P5	Locating Pin	1	Place circlip <P4> into housing <P1>	4
P6	Stud bolt	3	Place bearing <P3> into housing <P1>	4
P7	Cable tie	3	Spread circlip <P4> with circlip pliers <TL2>	10
P8	Oil drain plug	1	Press in bearing <P3> into housing <P1> with hydraulic press <TL1>	11
P9	Seal ring	1	Place pin <P5> in housing <P1>	5
P10	Venting pipe	1	Press in pin <P5> in housing <P1> with hydraulic press <TL1>	11
			Apply bolts M6x16 <P6> (3pcs.) in housing <P1>	22
			Screw in and tighten bolts M6x16 <P6> (3pcs.) into housing <P1> with torque wrench <TL4> and socket <TL5>	50
			Force on cable clip <P7> (3pcs.) on bolts M6x16 <P6> (3pcs.)	12
			Force in vent pipe <P10> into housing <P1>	5
			Apply sealing <P9> (1pc.) on oil drain screw <P8>	5
			Apply oil drain screw <P8> with sealing <P9> into the correct hole in the housing <P1>	5
			Screw in and tighten oil drain screw <P8> (1pc.) with torque wrench <TL4> and hexagon socket WS8 <TL6>	17

Pre-Assembly planet carrier				
P11	Planet carrier	1	Apply bearing grease <TL7> on bearing <P14> (3pcs.)	29
P12	Planet gear L/R	3	Clean planet gears <P12> (3pcs.) with cleaning equipment <TL7>	21
P13	Thrust washer	6	Stick bearing <P14> through planet gear <P12> (3pcs.)	11
P14	Needle bearing	3	Place thrust washers <P13> (6pcs.) on planet gear as shown in the picture	21
P15	Pin planet gear	3	Press in the balls <P16> (3pcs.) into the holes from the pins <P15> (3pcs.)	11
P16	Ball	3	Place planet gears <P12><P13><P13><P14> (3pcs.) into the carrier <P11>	43
P17	Sealing washer	1	Stick pins <P15><P16> (3pcs.) through carrier <P11> and planet gears <P12> (3pcs.)	22
P18	Axial (ring)	2	Place carrier <P11> in hydraulic press <TL1>	9
P19	Sun gear	1	Place sealing washer <P17> on carrier <P11>	5
P20	Adjustable washer	1	Press in sealing washer <P17> into carrier <P11> with hydraulic press <TL1> and tool for sealing washer <TL8>	17
P21	Carrier disk	1	Apply bearing grease <TL7> on axial bearings <P18> (2pcs.)	13
P22	Snap ring	1	Place axial bearing <P18> into carrier <P11>	8
P23	O-ring	1	Place sun gear <P19> into carrier <P11>	4
			Place axial bearing <P18> into carrier <P11>	8
			Place washer <P20> into carrier <P11>	4
			Place carrier disk <P21> into carrier <P11>	4
			Press carrier disk <P21> against carrier <P11>	4
			Fix carrier disk <P21> with snap ring <P22>	8
			Apply grease on O-ring <P23>	8
			Place O-ring <P23> into carrier <P11>	4
Pre-Assembly inner housing				
P24	Housing L/R	1	Place housing cover <P24> into hydraulic press <TL1>	10

P25	Shaft sealing ring housing	1	Clean area for radial seal <P25> and bearing <P27> with cleaning equipment <TL3>	16
P26	Oil guide	1	Place radial seal <P25> into housing cover <P24>	4
P27	Needle roller bearing	1	Press in radial seal <P25> into housing cover <P24> with hydraulic press <TL1>	11
			Place oil guide <P26> into the correct area from housing cover <P24>	8
			Apply bearing grease on bearing <P27>	10
			Place bearing <P27> into housing cover <P24>	4
			Press in bearing <P27> into housing cover <P24> with hydraulic press <TL1>	11
Assembly outer housing				
P1	Transmission housing out L/R	1	Place housing <P1> into hydraulic press <TL1>	11
P11	Planet carrier	1	Clean housing <P1> with cleaning equipment <TL3>	9
P24	Housing L/R	1	Clean carrier <P11> with cleaning equipment <TL3>	8
P28	Shaft sealing ring	1	Place carrier <P11> into housing <P1>	5
P29	Seeger circlip	1	Press in carrier <P11> into housing <P1> with hydraulic press <TL1>	11
P30	Hexagon bolt	9	Place circlip <P29> on carrier <P11>	4
			Fix circlip <P29> on carrier <P11> with circlip pliers <TL2>	10
			Place radial seal <P28> into housing <P1>	4
			Press in radial seal <P28> into housing <P1> with hydraulic press	11
			Clean housing <P1> and cover <P24> with cleaning equipment <TL3>	17
			Place housing cover <P24> on housing <P1>	5
			Apply hexagonal screws M6x20 (9pcs.)	32
			Screw in and tighten hexagonal screws M6x20 (9pcs.) with torque wrench <TL4> and hexagonal socket WS10 <TL9>	106

Main Assembly				
P1	Transmission housing out L/R	1	Clean housing <P1> with cleaning equipment <TL3>	8
P31	E-machine inverter complete	1	Clean E-Machine <P31> with cleaning equipment <TL3>	10
P32	Hexagon bolt 130	3	Place O-Ring <P34> on E-Machine <P30>	4
P33	Hexagon bolt 30	6	Place housing <P1> on E-Machine <P31>	6
P34	Side shaft	1	Apply hexagonal screws M8x30 <P33> (6pcs.)	41
P35	O-ring	1	Apply hexagonal screws M8x130 <P34> (3pcs.)	21
			Screw in and tighten hexagonal screws M8x30 <P33> (6pcs.) with torque wrench and hexagonal socket WS13 <TL10>	35
			Screw in and tighten hexagonal screws M8x130 <P34> (3pcs.) with torque wrench and hexagonal socket WS13 <TL10>	18
			Place shaft <P34> into housing <P1>	4
Leakage test - Oil filling				
P1	Transmission housing out L/R	1	Implement leakage test with leakage test device <TL12>	600
P31	E-machine inverter complete	1	Fill oil <TL11> (0,5l) in housing <P1>	18
P36	Sealing ring	1	Apply sealing <P36> on oil filling plug <P37>	5
P37	Oil filling plug	1	Apply oil filling plug <P37><P36> in housing <P1>	9
			Screw in and tighten oil filling plug <P37> with torque wrench <TL4> and hexagon socket WS8 <TL6>	12

References

[1] Hosseinpour and Chen, *Barriers to the Wide Adoption of Electric Vehicles : A Literature Review Based Discussion Barriers to the Wide Adoption of Electric Vehicles : A Literature Review Based Discussion* (2015), no. June 2016, 2015.

[2] NRDC, *The Paris agreement scam* (2017), 2017.

[3] Agency, 2018. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11.

[4] Cecere, Corrocher, *et al.*, *Price or performance ? A probabilistic choice analysis of the intention to buy electric vehicles in European countries* (2018), *Energy Policy*, vol. 118, no. March, pp. 19–32, 2018.

[5] Weldon, Morrissey, *et al.*, *Long-term cost of ownership comparative analysis between electric vehicles and internal combustion engine vehicles* (2018), *Sustain. Cities Soc.*, vol. 39, no. February, pp. 578–591, 2018.

[6] Policies, *Research for TRAN Committee - Charging infrastructure for electric road vehicles* (2018), no. June. 2018.

[7] Salah, Ilg, *et al.*, *Impact of electric vehicles on distribution substations: A Swiss case study* (2015), *Appl. Energy*, vol. 137, pp. 88–96, 2015.

[8] Chau and Li, *Overview of electric machines for electric and hybrid vehicles* (2014), *Int. J. Veh. Des.*, vol. 64, no. 1, pp. 46–71, 2014.

[9] Yang, Ali, *et al.*, *State-of-the-art electrified powertrains - hybrid, plug-in, and electric vehicles* (2016), *Int. J. Powertrains*, vol. 5, no. 1, 2016.

[10] Borthakur and Subramanian, *Design and optimization of a modified series hybrid electric vehicle powertrain* (2019), *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 233, no. 6, 2019.

[11] Wu, Zhang, *et al.*, *Powertrain architectures of electrified vehicles: Review, classification and comparison* (2015), *J. Franklin Inst.*, vol. 352, no. 2, 2015.

[12] Pro2Future, [Online]. Available: http://www.pro2future.at/start-en/.

[13] Bloder, *Personal Interview on 16.04.2019* (2019), 2019.

[14] Bertsche, Naunheimer, *et al.*, *Automotive Transmissions Fundamentals, Selection, Design and Application* (2013), vol. 53, no. 9. 2013.

[15] Bahandari, *Design of Machine Elements* (2016), *Des. Mach. Elem.*, vol. Third edit, 2016.

[16] Gears, *Introduction to Gears First Edition* (2006), 2006.

[17] HOUCKE, *Bearing arrangements*.

[18] NTN, *Ball and Roller Bearings* (2015), 2015.

[19] Zhang and Mi, *Automotive Power Transmission Systems* (2018). 2018.

[20] Gai, Kimiabeigi, *et al.*, *Cooling of automotive traction motors: Schemes, examples, and computation methods* (2019), *IEEE Trans. Ind. Electron.*, vol. 66, no. 3, 2019.

[21] Mahale, Patwardhan, *et al.*, *Dynamic Analysis of an Automatic Transmission* (2007), *SAE Tech. Pap.*, vol. 2007–Janua, no. January, 2007.

[22] SKF, *Industrial Sealing Solutions* (2014), 2014.

[23] Khayal, *Types of Seals* (2017), 2017.

[24] Brillinger, Hadi, *et al.*, *Adaptive Smart Assembly Concept in e-Mobility : A Research*

Direction Key Words : Adaptive Smart Assembly , e-Mobility , Cognitive Production , High Variety Batch Production , Level of Practical Application (LoPA). (2019), 2019.

[25] Dukić, Česnik, *et al.*, *Order-picking methods and technologies for greener warehousing* (2010), *Strojarstvo*, vol. 52, no. 1, 2010.

[26] Beluško, Hegedüš, *et al.*, *Creating Visual Work Instructions to Ensure Safe and Fluent Operation of the Semi-Automatic Production Lines* (2016), *Open Eng.*, vol. 6, no. 1, 2016.

[27] Ullrich, *Automated guided vehicle systems* (2015), vol. 2, no. 4. 2015.

[28] Tingelstad and Egeland, *Robotic assembly of aircraft engine components using a closed-loop alignment process* (2014), *Procedia CIRP*, vol. 23, no. C, 2014.

[29] Gravel and Newman, *Flexible robotic assembly efforts at Ford Motor Company* (2001), *IEEE Int. Symp. Intell. Control - Proc.*, no. February, 2001.

[30] De Carlo, Arleo, *et al.*, *Layout design for a low capacity manufacturing line: A case study* (2013), *Int. J. Eng. Bus. Manag.*, vol. 5, no. SPL.ISSUE, 2013.

[31] Kassir, *Principles of Industrial Engineering* (2015), 2015.

[32] Ohno and Nakade, *Analysis and optimization of a U-shaped production line* (1997), *J. Oper. Res. Soc. Japan*, vol. 40, no. 1, 1997.

[33] Heilala, *Use of simulation in manufacturing and logistics systems planning* (1999), *Proc. VTT Manuf. Technol.*, no. January 1999, 1999.

[34] Mourtzis, Doukas, *et al.*, *Simulation in manufacturing: Review and challenges* (2014), *Procedia CIRP*, vol. 25, no. C, 2014.

[35] Kikolski, *Identification of production bottlenecks with the use of Plant Simulation software* (2016), *Eng. Manag. Prod. Serv.*, vol. 8, no. 4, 2016.

[36] Bangsow, *Tecnomatix Plant Simulation: Modeling and Programming by Means of Examples* (2016). 2016.

[37] Law, *How to build a valid and credible simulation models* (2008), *Proc. 40th Conf. Winter Simul.*, 2008.

[38] Law, *How to build valid and credible simulation models* (2009), *Proc. - Winter Simul. Conf.*, pp. 24–33, 2009.

[39] Rosenback, *Antecedents and Obstacles To Total Cost of Ownership Analysis in Industrial Marketing — a Case Study* (2013), 2013.

[40] Parkhi, *Total Cost of Ownership_Overview* (2015), 2015.

[41] Weinzerl, Jeitler, *et al.*, *Skype Interview on 15.05.2019* (2019), 2019.

[42] Safizadeh, Ritzman, *et al.*, *An empirical analysis of the product-process matrix* (1996), *Manage. Sci.*, vol. 42, no. 11, 1996.

[43] Bloder, *Personal Interview on 12.06.2019* (2019), 2019.

[44] Robots, 2019. [Online]. Available: https://www.universal-robots.com/products/.

[45] Sirovetnukul and Chutima, *The impact of walking time on U-shaped assembly line worker allocation problems* (2010), *Eng. J.*, vol. 14, no. 2, 2010.

[46] Abdul Hadi, *Master thesis: Adaptive Assembly Concepts for Low Volume Production Based on Two Case Studies* (2019), 2019.

[47] Klaus, *Skype Interview on 22.05.2019* (2019), 2019.

[48] Rampe, *Bachelorarbeit* (2018), 2018.

[49] Heilala, Helin, *et al.*, *18th ICPR paper : TOTAL COST OF OWNERSHIP ANALYSIS FOR MODULAR FINAL ASSEMBLY r P Fo r R w On ly* (2010), 2010.

[50] Jeitler, *Personal Interview on 01.10.2019* (2019), 2019.