Parametric evaluation and cost analysis in an e-axle assembly layout

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Abstract. Over the years, e-mobility has scaled exponentially, specifically automobiles, and is seen as the future. In this paper, implementation of specific adaptive technologies into the assembly line has been performed and is presented in the form of case study. The architecture and model of these technologies utilised are presented and their benefits on assembly line. Thus, indication is proven towards building a highly flexible, adaptive and cost-effective assembly line. Evaluation techniques such as FMEA, technomatix simulation and Level of Automation (LoA) study are performed to prove the improvements in qualitative, adaptive and an increase in automation levels when compared to previous manual assembly. Furthermore, the variances in e-axles are depicted with reference to e-axles from eminent electric automobile manufacturers. This is followed with a generalised assembly procedure and a cost model for the e-axle assembly. The results depict the adaptability achieved along with cost benefits when compared to an automated assembly line.

Keywords: Adaptive assembly of e-axles · E-mobility · Qualitative and cost analysis.

1 Introduction

Since the beginning of industrialisation, manufacturing of products has been moving towards digitisation. With digitisation, the products are manufactured much faster, cheaper, and moreover, in large quantities. However, products with lower batch size are yet being manufactured without the techniques of automation due to high costs. On the other hand, the products manufactured in Europe cannot be compared to low-wage countries in terms of price. Hence, in order to counterbalance the increased production costs in Europe to the customer, additional benefits must be generated for the customer, such as: high quality, shorter delivery times, etc. Adaptive production systems can be one such approach to reduce the production costs. They make it possible to manufacture different types of products with the same production equipment at relatively low costs.

In this project, a novel, highly flexible assembly system was developed for various electric drive systems in order to manufacture them inexpensively and with high precision. The strengths of man and machine have been optimally combined. While the assembly worker can act instantly with smartness and flexibility as the changes in product occur, machines such as robots on the other hand, are very well suited for repetitive tasks. In this project, the best of these two sides were combined so that the varying activities can be implemented quickly by the worker.

Equipping the assembly line with cognitive features allows the inexperienced workers to be quickly trained. This is achieved by analysing the assembly activities that are and will be performed by workers in the vicinity (assembly stations) and, if required, support them with informative and assistive systems. These informative and assistive systems are for example pick-to-light, pick-to-voice, screens, etc.

The implementation of a completely automated assembly line for a small batch size and high variety products such as e-axles can have many drawbacks. Mainly because of the tiresome programming and initial-setup of robots and the high costs associated with it for an automated assembly line. Hence, the aforementioned technologies acts as a counterbalance to increase the adaptivity as well as maintaining the costs of the assembly line. Moving forward, this paper presents the results in the form of case study where three selected adaptive technologies have been implemented and their impacts on the assembly line with respect to various parameters. This paper corresponds to stage C of the study from figure 4. The final results have been presented which denotes the research output of the initial implementation of study.

2 State of the art

In this section, research findings along with the state of the art is briefed. The study of E-axles is presented in the first section. As this paper is a continuation of previous papers, the next section briefly describes the previous publications. This section explains the research and initial results in previous papers that could be linked to the current paper. The next section explains the selected adaptive technologies for the first full implementation into the assembly line. Finally, the state of the art with respect to the basic cost model in an e-axle and the simulation approach the is followed is briefed in last section.

2.1 The product: E-axle

Prior to explaining the technologies that have been selected for implementation and further study, it is necessary to explain the product, e-axle in brief. As described in figure 1, an electric powertrain as a whole combines the e-axle and energy storage system. The focus area of this assembly layout is only the e-axle. E-axle further involves the energy and torque conversion systems. Moreover, the form of energy transformation from one module to another is shown.

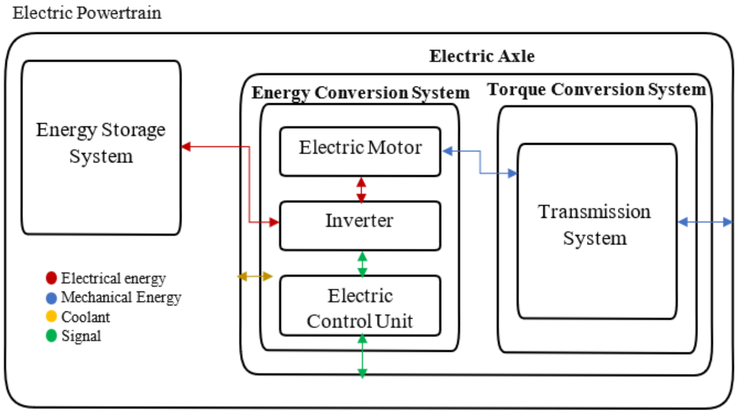


Fig. 1. Functional modules of e-axle.

The e-axles can be derived on the basis of energy conversion (figure 2) and torque conversion (figure 3) system. Two such e-axles (A and B) that are assembled on this layout along with e-axles of acclaimed manufacturers are depicted in these figures. The flowcharts have also been explained in [1] by the author.

As the variety in e-axles is distinctly understandable from the figures, further variety can also be generated. However, with respect to the current e-axle market, majority of which fall under these classifications. The next step for ideation is to generalize the assembly steps with respect to this variety which is followed in the next section.

2.2 Continuation study

For a successful implementation of an adaptive assembly line, suitable technologies must be implemented. These technologies must be chosen to using criterion based on their automation, adaptivity (i.e., flexibility), and cost levels. Abdul Hadi et al describes these technologies and concepts in [2]. Four concepts have been derived with sub-technologies that have been clustered into an LoPA (Level of Practical Application) matrix. These concepts were further honed during the implementation phase by building the system architecture for respective technologies. As seen from figure 4, paper 1 represents this study of deriving the concepts and technologies and hence building a LoPA matrix. Moreover, the assembly layout prior to initiation of study and the product were analysed in this stage. The initial results of which are presented in [2].

A step by step approach was followed to implement the first few technologies into the assembly line. Paper 2 from figure 4 was the focus of study in this paper. Initially, only one station was equipped with human-machine interaction and an another station for data-driven bearing test rig (BTR) in an e-axle. The human-machine interaction involved a collaborative robot i.e., cobot. The cobot

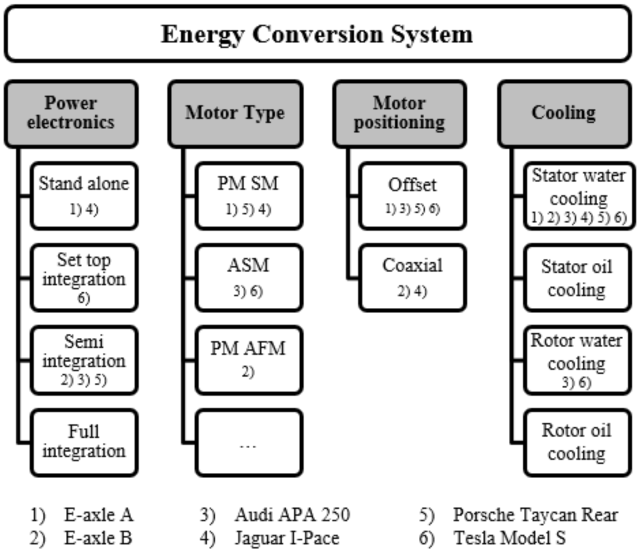


Fig. 2. E-axle classification based on energy conversion.

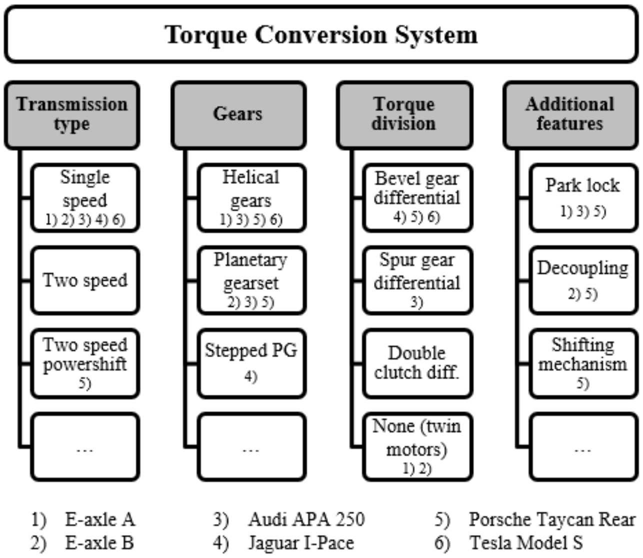


Fig. 3. E-axle classification based on torque conversion.

performed the high variety assembly of bearings in an e-axle, the sealing application, and bolting operations for combining the two sides of e-axle housing. The bearing test rig is a reliable method to analyse the durability, Noise Vibration Harshness (NVH) behaviour, thermal behaviour, and prediction of other properties based on the quality and assembly tolerances of the bearing in an e-axle. Both these case studies are being published in the paper titled "Implementing cognitive technologies in an assembly line based on two case studies" under the Procedia CIRP 2020 proceedings [1]. This paper depicting the detailed two case studies is a follow-on to the previous publication by Abdul Hadi et al in [2].

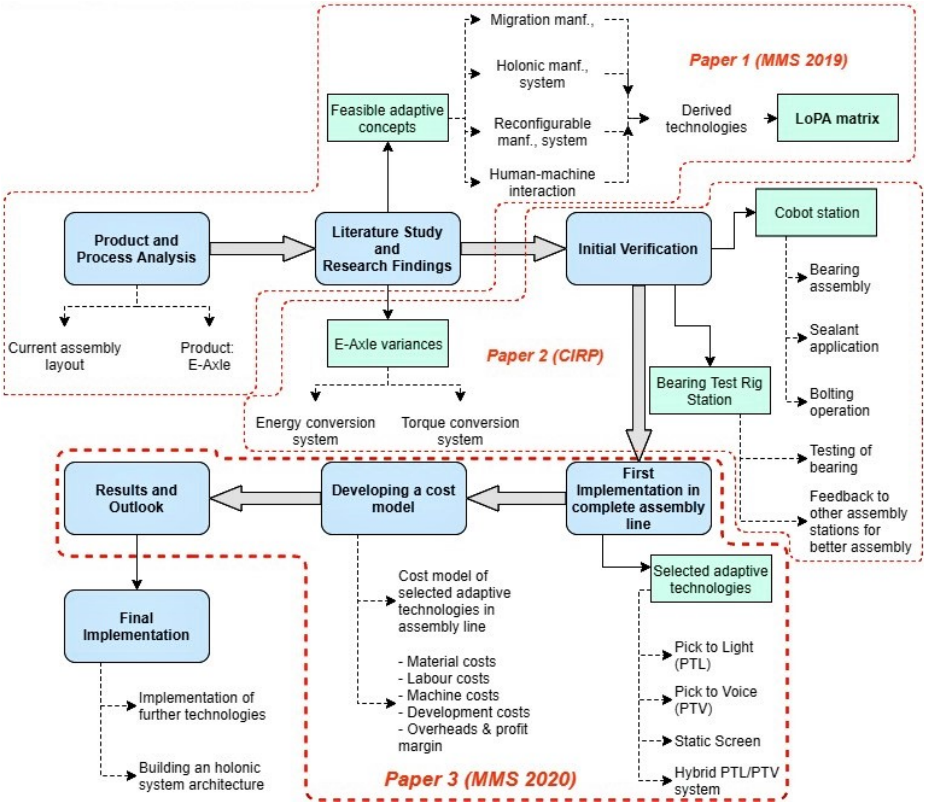


Fig. 4. Approach of study.

2.3 Selected adaptive technologies

The LoPA matrix depicted in [2] classifies the technologies based on practicality in the assembly line. These technologies have also been categorised on their technology readiness level (TRL) [3]. Of the classified technologies, some of the technologies under the highest level of practical application are selected for initial implementation into the assembly line. These technologies are:

- Pick to Light (PTL) technology
- Pick to Voice (PTV) technology
- Static Screen
- Hybrid PTL/PTV system

These technologies are chosen to follow a linear move towards automation from a complete manual assembly. Studies have shown that a failure of the assembly line occurs when a sudden transition is made from manual to a completely automated system [4]. Hence, three technologies along with the already existing cobot and BTR station is implemented into the entire assembly line of e-axle.

Pick to light technology. The PTL system have increasingly become more common over time. The market of pick to light was estimated at \$304.1 million in 2016 and is depicted to increase up to \$538.2 million by 2023, at a rate of 8.84% [5]. These have progressively been acceptable in all warehouse logistic activities and enhancing the level of automation [6]. However, for their implementation in the area of assembly processes, the design and architecture must be restructured. The current e-axle assembly has over 25 assembly steps in each station. As shown in figure 5, the multiple boxes in the assembly station are monitored via infrared (IR) sensors and LED light arrays which indicate the part to be picked. They are controlled via a micro controller and monitoring to pick the right part is calculated by the distance x and signal to the receiver. Moreover, the boxes are classified into ABC principle based on their usage in the assembly [7], [8].

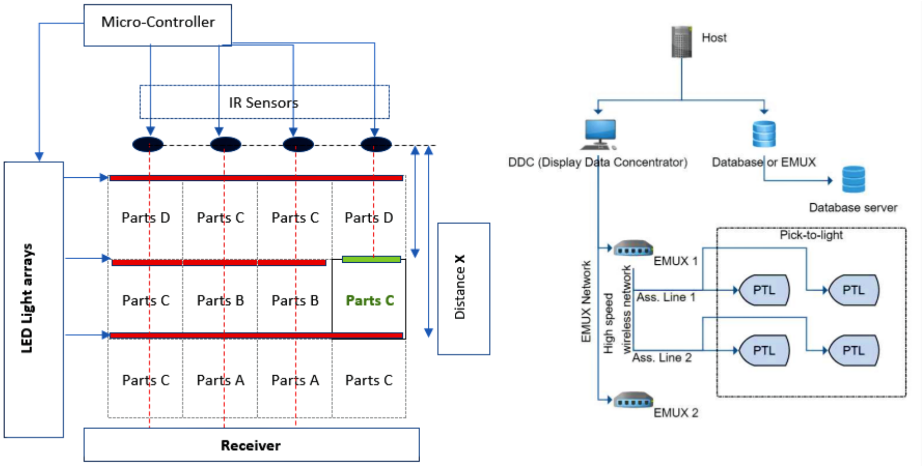


Fig. 5. PTL system and its architecture.

The levels of the PTL architecture are as follows. Level 1: The DDC (display data connector) receives information of the logic process order of picking from the host system. This DDC receives the orders and transfers the prepared data to the Multiplexer or EMUX (Electrical Multiplexing System). Level 2: The EMUX is the link between the assembly stations and the DDC. At one hand, it sends the received data from DDC to the stations and on the other, it transfers the done operations to the DDC and the database, which triggers the next set of operation. Level 3: Are the light displays (or just displays) which denote the next assembly operation to be performed.

Pick to voice technology. The use of smart devices in production has increased over time. Many smart devices are entering the market and it is expected to increase at a rate of 11.9% until 2023 [5]. As in the PTL system, the architecture is built on the same model. However, there are multiple access points in an assembly area. These access points then wirelessly communicate with each individual at a workstation. Through this technique, it is possible to instruct, guide, and monitor the worker even when his/her view is elsewhere. Also, these devices are a promising technology for visualisation of technology and knowledge transfer [9]. There are several benefits for usage of such technologies. Most importantly, no initial training is required. A constant monitoring and feedback are an additional advantage with such a system.

Static screen. Most of the industries have the process steps or instructions placed close to the worker. Among these are those that still have a hard copy of these process steps fixed onto the workstation. However, utilization of a digital method such as static screen is quite scarce in an assembly line. This modality is quite useful and important to transport complex information and decisions via text, images, or also video sequences [10]. The detailed process steps and information can be displayed at a static/movable screen placed ahead of the worker [11]. Fasth describes that by using a "mobile information carrier" for assembly processes increases the productivity and quality [6], [12]. Moreover, it is beneficial on the perspective of costs. The information is consistently within reach and the cost to look an additional time is much lower if the instructions are at a visible height. It also enables a proactive work environment. The static screens are positioned on a special rack system in a way that the screens can be maneuvered along the axis (vertically) and an angle depending on the worker setting.

Hybrid PTL/PTV system. A combination of the aforementioned PTL and PTV system was experimented during the simulation study. With an additional investment of having both technologies, the productivity gain was much higher and over-weighed these investment costs. The productivity as well as rework of the products have considerably reduced which is explained in detail in further sections. The hybrid system has a high potential for increasing the productivity with 5.7%. Moreover, static screen increases productivity by 3.4% and finally PTL with 3.7%. The reduction in rework percentage by implementing static screen is 3.6%, PTL system reduces by 1.5%, PTV system reduces by 1.8% and finally the Hybrid system reduces the rework by 3.2%.

2.4 Basic cost model and Simulation study

Implementing these aforementioned adaptive technologies into an assembly line for e-axle for increasing adaptivity will raise the initial costs of the assembly line. As seen in figure 6, beside labor, machine, material and development costs, the costs for adaptive technologies needs to be considered. The costs of each position cannot be shown due to confidentiality.

On the other hand, the higher adaptivity of the assembly line leads to higher variances of e-axles which can be assembled on the line which thereby reduces the specific adaptive technology costs per axle. In addition to this, the reduced possibilities for failure occurring with manual assembly operations must be considered. To do so a FMEA analysis of a adaptive assembly line with and without these technologies will be carried out and compared.

The third important issue is the throughput. It determines the costs strongly. Due to the assembly of different types of e-axles, such as A and B, at one assembly line, many bottlenecks may occur. Hence, a tecnomatix simulation model of the adaptive assembly line will identify the throughput with respect to the product mix of e-axle A and B.

Furthermore, a simulation of the assembly layout with all the parameters and constraints is a step closer to digital twin. The simulation model can be used to visualize the assembly in real-time [13], [14]. Tecnomatix plant simulation was utilized for building the assembly model. In this respective case study, with the help of simulation approach, many criterion were determined:

- the order in which various e-axles must be assembled
- determining the implementation of specific adaptive technologies at specific stations
- calculation of throughput of individual e-axles

Moreover, the cost analysis, simulation study, FMEA, and LoA (Level of Automation) study depict the improvements of an assembly line post the implementation of adaptive technologies. Also, the initial simulation study and FMEA performed in [2] indicate the results of only one e-axle being assembled on the manual assemble line. However, the current analysis considers the higher variety of e-axles with considerations of improved assembly layout, implementation of technologies and a better cost model.

3 Research gap

With the product being explained in chapter 1 and it's variances, it was necessary to determine the befitting technologies to implement into the assembly line.

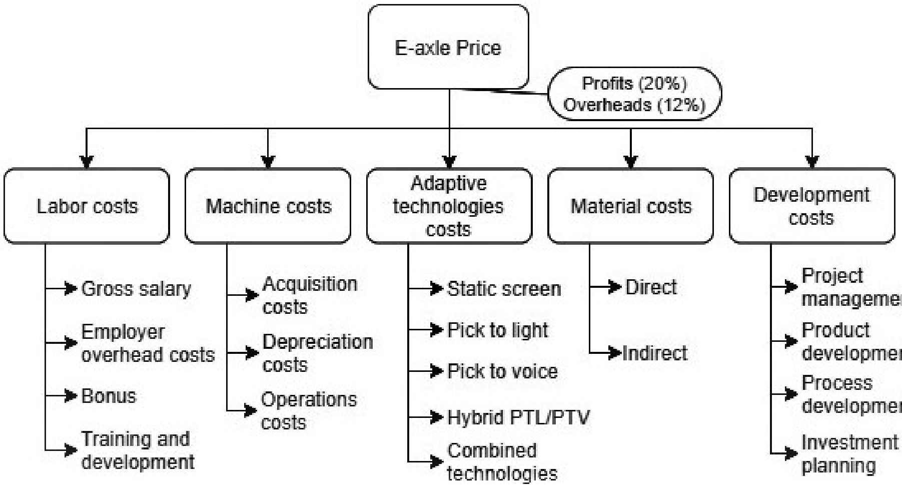


Fig. 6. Cost model.

Chapter 2 explains the technologies involved for initial implementation along with one of the architecture. The next phase is the implementation of these technologies in a generalized assembly layout. The linkage between the two must be formed for building the assembly layout.

Much literature and methodologies are not available in this scientific field as the concept of e-mobility, specifically e-axles, is an emerging one. And developing an assembly layout for high variety is a challenging aspect. Hence, this paper depicts a successful approach in creation of an interrelationship between the technologies, adaptivity, automation, and quality. Moreover, the low volume and high variety assembly line which can generally be used even for a prototype e-axle assembly would be an outcome of this research.

4 Methodology

The methodology or an approach in developing the assembly layout with the said technologies is followed a straightforward approach as seen in figure 7. Post the product and feasible technologies analysis, a feasibility check is performed to indicate if the researched technologies fit into the assembly line for the product, e-axle. Initial implementation is followed where a trial run is performed by implementing technologies on two stations. An assembly layout is ideated for assembling this high variety of e-axles, i.e., high flexibility.

Methods time measurement (MTM) is followed for calculation of ideal assembly time required for each task. With the help of this timings, a simulation model is built. This is done prior to implementation of further technologies in assembly line to denote the throughput and alter the scheduling of e-axles. The said technologies in section 2.3 are implemented in the assembly stations. A cost model is built based on these technologies and throughput. This serves as a basic model before the implementation of further technologies. Evaluation procedures such as LoA, FMEA, etc., are followed to monitor the assembly line. A feedback system from the technologies are also generated and monitored for anomalies. This feedback system helps in further honing of the e-axle assembly to increase the throughput and quality.

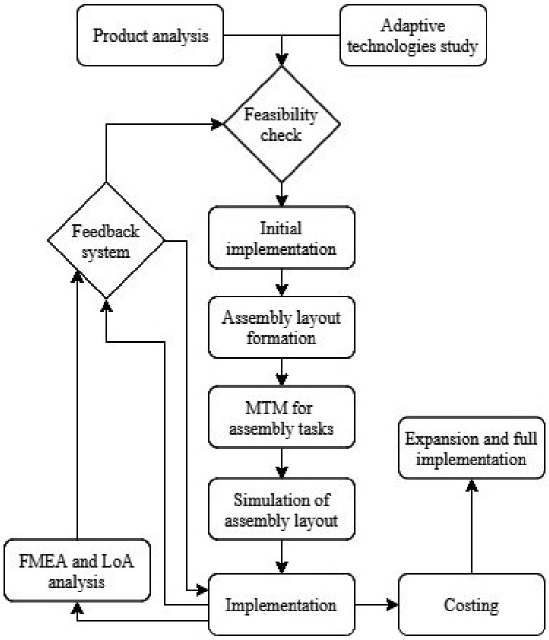


Fig. 7. Methodology.

5 Assembly layout formation

Similar to the ICE (internal combustion engine), an electric powertrain, thence e-axles, can have a huge variety. Hence, e-axles with similar product structure must be ideated and clustered, which thereby follows a same sequence of assembly process. The assembly steps common to most of the e-axles are derived which have been explained in this chapter. Further, a suitable layout is ideated for assembly of this immense variety of e-axles. The adaptive technologies that were selected for implementation into the assembly line have been explained in the previous section and have been implemented. These technologies impact the assembly line tremendously in improving the process which has been explained going further.

5.1 Generalization of assembly steps

The e-axle assembly follows a similar pattern of assembly tasks that is required. However, some of the e-axles have additional tasks that must be performed and vice versa. In case of additional tasks, the e-axle or product moves to a universal station. The detailed aspects of each station has been explained in the table 1. The assembly is classified over seven stations along with the end of line (EOL) test.

Table 1. Clustering of assembly tasks.

No.	**Station**	**Tasks involved**	**Necessary equipment**	**Complexity**
1	Pre-assembly station	Interference fitting, placing snap ring	Hydraulic press, heating device	Medium to high
2	Motor pre-assembly	Interference fitting, placing snap ring, small part installation, bolting and sealing application if necessary	Hydraulic press, heating device	Medium
3	Rotor - stator housing assembly	Fitting rotor and stator, fitting shaft if necessary	Centring device	High
4	Main transmission assembly	Installation of shaft, actuators, park-lock, shifting mechanism and small parts	Hydraulic press, measurement tools	Medium
5	Closing station	Apply sealant, bolting, and inverter mounting	Cobot station	Low
6	EOL test station	Connect and disconnect	EOL equipment	
7	Universal station	Special operations, buffer station and rework		

As shown in table 1, each station also indicates the assembly tasks it involves. The necessary equipment and the complexity level have also been determined. The complexity level is determined with the time taken for assembly due to it's complexity of the tasks. These levels have also been verified through simulation. Station 6 is an EOL test station where one in ten e-axles at random are tested for its performance. The universal station i.e., station 7, as mentioned prior, performs special operations or acts as a buffer station.

5.2 Formulation of new layout

With the aforementioned 7 stations, a layout must be ideated for the assembly process. Several layout concepts were generated that could be implemented for the assembly of e-axles. Also, the mentioned four concepts in [2] were to be implemented in this assembly line. The holonic communication was achieved via the AGVs (automatic guided vehicles), where they interact with the universal station wirelessly [2]. The mentioned adaptive technologies in section 2.3 were implemented with the concepts [2] to generate a highly flexible assembly layout.

Value benefit analysis [15], [16] is a technique used for evaluation and detection of functions of products, systems, or organisations. It validates these functions, characterises and structures the outlining functions of the system. Further, it also involves cost analysis for accessing the cost of this system. Finally, a number is generated which depicts the value of the system. Higher the number, the greater is the value of the system.

The ideation of the layout was done along with the representatives from the company. Over six layout concepts were derived and the value benefit analysis for each was followed to derive one final concept. The sketch of layout has been described in [1] and shown in figure 8. Here, the bearing test rig station which is placed along with the universal station for depiction purposes, have feedback loops to the stations involving bearing assemblies as this is a crucial assembly in an e-axle. Use cases of BTR and cobot station (station 5) are well explained in [1].

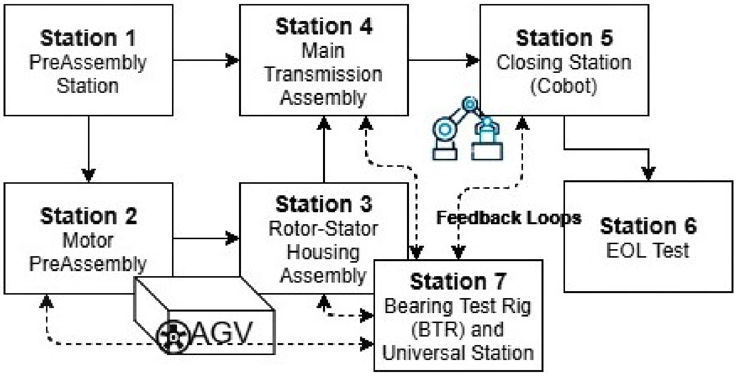


Fig. 8. Assembly layout.

6 Simulation study and costs

In this chapter, the results of the simulation study are seen with respect to each technology and combination of these technologies. Also, the sequence of assembly of e-axles is described. The technologies have been iterated in the simulation study to best suite the individual assembly stations and also to mitigate the error indicated by FMEA of the considered assembly line. The next section describes the costs in brief for the implemented e-axle assembly layout. Moreover, the detailed costs of individual technology is not shown due to the reason of confidentiality as indicated before.

6.1 Simulation study

Initial simulation. The initial study for the assembly layout, prior to implementing adaptive technologies and layout variations revealed few loopholes. The initial layout was only designed for one type of e-axle. The throughput was 3895 e-axles per year. This simulation results showed a negative deviation of 0.5% with the actual implemented output. This possible potential for this deviation was the walking distance of the worker which was not considered and the moving of parts from one station to another. However, this deviation was later reduced in the further models.

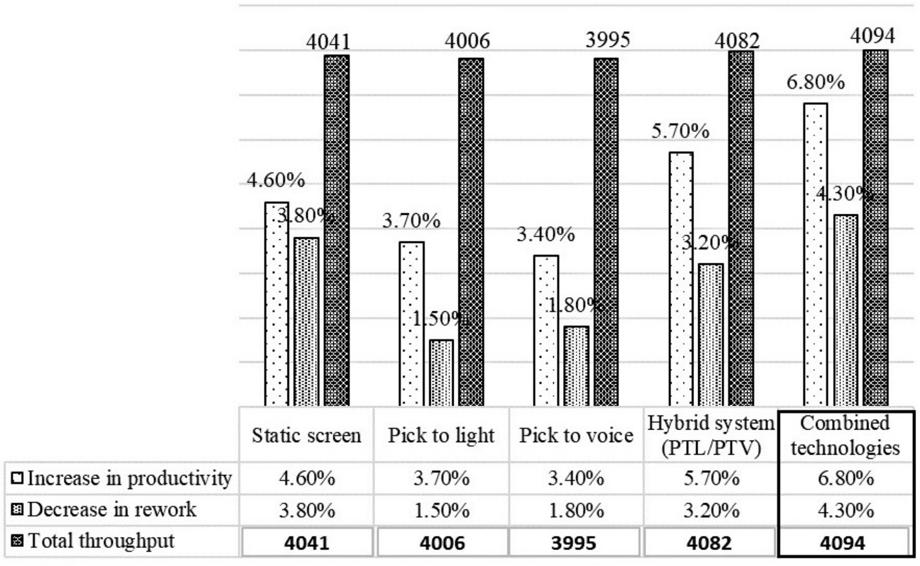
Sequencing. Since the variety of e-axles assembled is more than one, sequencing them is an important aspect to achieve higher and faster throughput. The simulation approach has aided in identifying the best quantity of an e-axle to assemble prior to moving to the next set of e-axles. As the batch size per day is quite low, e.g., 10-20 e-axles per day for each variety, it is necessary to determine the minimum number of e-axles to assemble before the switch to another e-axle. Considering two varieties of e-axles are assembled in a day, the minimum number of e-axles to be assembled is four. Once four e-axles have been assembled, a switch can be made to another variety. However, this is the least number for assembly of one variety. If only one e-axle is assembled per day, the throughput is higher. But since the goal is to depict an adaptive assembly line, the former variance is used. Figure 9 depicts the results considering this sequence approach of four e-axles per variety before a change is made to another one. [2] describes the 3 types of e-axles and their assembly times utilized for the simulation approach.

Adaptive technologies. Abdul Hadi et al describes the RPN numbers of the assembly process prior to implementing adaptive technologies in [2]. The considered 3 adaptive technologies, explained in section 2.3, have been implemented in the assembly line. The benefit of each technology in the assembly line is shown in the table below.

Results. With the help of a simulation model, individual increases in productivity and throughput were determined. The technologies were combined to determine the increase in throughput. Figure 9 depicts the results of study. Also, sequencing of e-axles is also explained to achieve maximum throughput. With the help of these studies, the rework has also reduced which is an important aspect to depict the qualitative improvements.

6.2 Costs

The cost of building a flexible assembly line is usually considered to be higher. It is much higher than a dedicated assembly line for assembly of a single product [17], [18]. Moreover, utilising automation technologies for a flexible line further adds to the costs of assembly. Hence, it is crucial to explain the costs of e-axle



	Static screen	Pick to light	Pick to voice	Hybrid system (PTL/PTV)	Combined technologies
☐ Increase in productivity	4.60%	3.70%	3.40%	5.70%	6.80%
▤ Decrease in rework	3.80%	1.50%	1.80%	3.20%	4.30%
▩ Total throughput	**4041**	**4006**	**3995**	**4082**	**4094**

Fig. 9. Results from simulation study.

including the technologies involved to depict the cost advantage of an adaptive assembly line over flexible and dedicated lines.

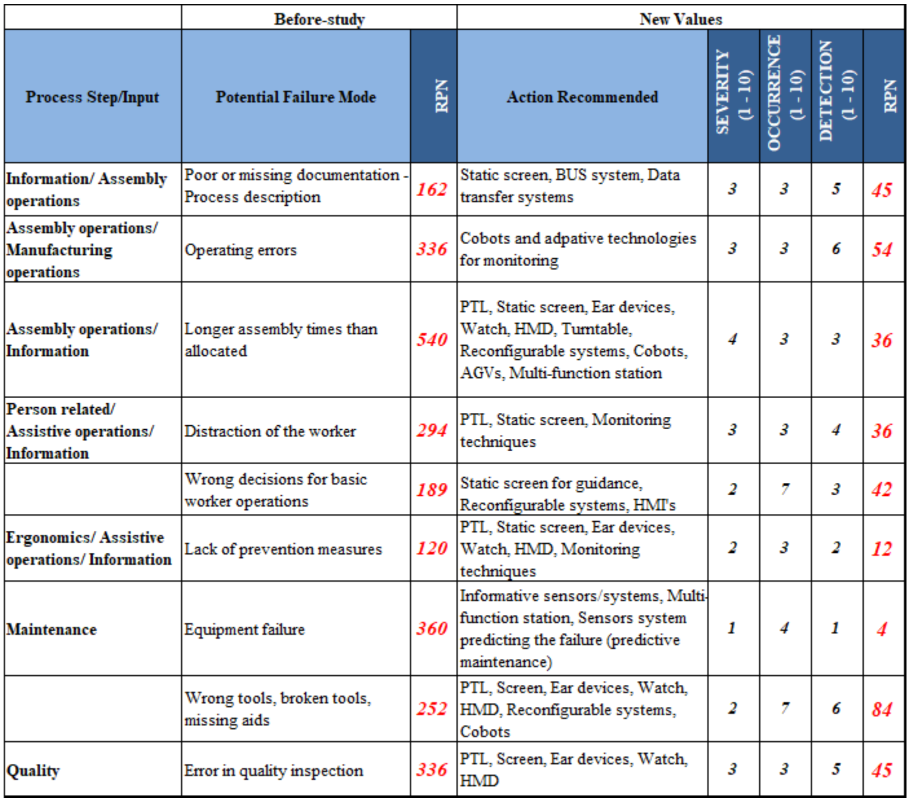
A cost model is an elaborate topic comprising of many aspects and considerations. As indicated from the figure 9, the considered technologies have a positive impact on the productivity, rework and hence, throughput. Generally, the calculated break-even point between the investment of these technologies and the returns generated is between a year up to a year and a half. Considering the lifetime of these technologies to be over 3 years, these technologies best fit into the cost-effective adaptive assembly line. The further considerations that have been made are the access points for these wireless devices, database systems and the initial implementation costs. The central warehouse execution system (WES) monitors and controls these devices along with knowledge and information transfer to the assembly stations. Moreover, there are further several subtopics under each of the sections in cost model which are not depicted due to complexity.

As the throughput of e-axles have increased along with the flexibility, costs have been reduced by a certain percentage. Approximately, for e-axle A, a 2% reduction in costs is seen indicating the benefit of adaptive technologies in the assembly line. Elaborative results with the percentages can be seen in figure 9.

7 Results and Outlook

The paper begins with explaining the e-axle market in Europe. It depicts the importance of this study as the e-axle market is an emerging one in the field of e-mobility. Moreover, this paper is a continuation of previously published two papers [2], [1] as explained from the figure 4. The technologies derived and the concepts generated have been verified over the course of study. Three technologies have been selected for the initial implementation and to develop a cost model. This is done to determine the impact of these technologies on the assembly line prior to implementation of further adaptive technology models. This approach is also followed to negate the technology jump that would cause disruption for the workers and assembly process.

An e-axle can have vast variety similar to that of ICE and mostly depending on the automobile manufacturer. This variety generally depends on the energy and torque conversion systems as shown in the figures 2 and 3. This variety was analysed and assembly tasks in each e-axle were further clustered. They were clustered into stations and the necessary tasks and equipment involved was derived. Finally, a new assembly layout was formulated with the help of value benefit analysis. A rough overview of the layout is shown in figure 8. The feedback loop is generated, most importantly from bearing test rig and the end of line testing station to constantly improve the e-axle assembly. The evaluation study



	Before-study		New Values				
Process Step/Input	Potential Failure Mode	RPN	Action Recommended	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
Information/ Assembly operations	Poor or missing documentation - Process description	162	Static screen, BUS system, Data transfer systems	3	3	5	45
Assembly operations/ Manufacturing operations	Operating errors	336	Cobots and adpative technologies for monitoring	3	3	6	54
Assembly operations/ Information	Longer assembly times than allocated	540	PTL, Static screen, Ear devices, Watch, HMD, Turntable, Reconfigurable systems, Cobots, AGVs, Multi-function station	4	3	3	36
Person related/ Assistive operations/ Information	Distraction of the worker	294	PTL, Static screen, Monitoring techniques	3	3	4	36
	Wrong decisions for basic worker operations	189	Static screen for guidance, Reconfigurable systems, HMI's	2	7	3	42
Ergonomics/ Assistive operations/ Information	Lack of prevention measures	120	PTL, Static screen, Ear devices, Watch, HMD, Monitoring techniques	2	3	2	12
Maintenance	Equipment failure	360	Informative sensors/systems, Multi-function station, Sensors system predicting the failure (predictive maintenance)	1	4	1	4
	Wrong tools, broken tools, missing aids	252	PTL, Screen, Ear devices, Watch, HMD, Reconfigurable systems, Cobots	2	7	6	84
Quality	Error in quality inspection	336	PTL, Screen, Ear devices, Watch, HMD	3	3	5	45

Fig. 10. Post-implementation FMEA (extracted).

is followed in the next section. A simulation model has been built up to determine the improvements in the assembly line. Simulation in technomatix proves that with the implementation of the selected technologies, there is an impact on productivity, rework and throughput as shown in table 2.3. Moreover, an FMEA of the after implementation was also done to determine the decrease in the risk priority number (RPN) i.e., the errors in the assembly line. The initial study of this FMEA prior to implementing the adaptive technologies is shown in [2]. The FMEA done after the implementation of assembly technologies is shown in extracted table 10. As it is depicted, the RPN numbers have significantly reduced indication an increase in quality of the assembly line. Further, an increase in level of automation, i.e., physical and cognitive automation levels, is significantly noted.

The cost model developed for the e-axle assembly depicts the investment required for implementation of an adaptive assembly line. As predicted, the cost of implementing an assembly line of this type is much easier and cheaper when compared to an automated line. The devices and technologies used in an adaptive assembly line are mostly assistive and informative systems. Thus, the costs are cheaper than implementing robots and automated machinery. Moreover, the flexibility is much higher in the case of these systems.

Further study must be done for developing an holonic communication system, i.e., wireless communication, between the stations. A system architecture must be built at first, tested and then implemented. Since further adaptive technologies must be implemented, the holonic architecture system is necessary. Moreover, the use of collaborative robots (cobots) must be increased, which is currently being used for bearing assembly, sealing and bolting operations. This would further decrease the qualitative errors and increase the productivity.

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