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Optimal Level of Automation in the Automotive Industry

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Abstract. **Strong competition on the global automotive market is forcing car manufacturers rethink their strategic approach to manufacturing. In order to be competitive, companies need to manufacture variety of new car models at the lowest cost. This requires manufacturing systems to be flexible to accommodate product variations and economically viable. Automotive industry has been traditionally highly automated and not particularly flexible in terms of final products. Despite many developments in the area of flexible manufacturing systems, they could not reach their potential, especially in the final car assembly, mainly due to high system complexity, which also results in high costs of automation. A balanced combination of manual and automated processes increases flexibility, reduces manufacturing costs, provides high quality and throughput. In the view of the above, an optimal level of automation of manufacturing systems can only be obtained if all relevant aspects of the manufacturing process are taken into account and optimum levels in terms of cost, productivity, quality and flexibility are reached as proposed in the methodology of the Fraunhofer Institute. This approach was applied for analysis of the final car assembly lines at Volkswagen AG.**

Index Terms—**Automation level, Manufacturing economics**.

I. INTRODUCTION

Today, the automotive industry is the epitome of mass production, mass marketing and mass consumption. Production technology becomes more significant due to the ever-growing number of suppliers and competitors in the market. Increasing globalisation causes stronger competition among the producing companies. Markets convert from sales to consumer markets. Hence, an urge for progressive automation arose in the past, since it seemed to be the only strategy to be competitive. However, a high level of automation can lead to less flexible automation systems and the products are difficult to customise or to extremely complex automation systems, which are expensive. According to the studies done by Fraunhofer Institute, 36% of the companies, which have had experiences with automated solutions, are of the opinion that they exaggerated automation in the past [1]. Therefore, the choice of level of automation of a production system is an important management decision.

The Volkswagen AG *(VW)* procedure for introducing a new vehicle is represented in Fig. 1 showing that plant location plays an important role in process planning and preparation. The choice of plant location depends, among others, on the personnel and energy costs, the level of education, skills and motivation of personnel, and the market conditions. On the other hand, the plant location determines the level of automation of assembly lines.

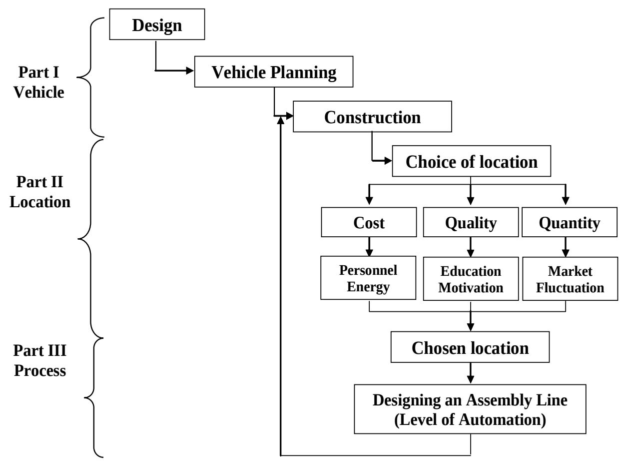

Figure 1: General procedure for introducing a new vehicle

The analysis of the assembly lines of *VW* at the three production sites was done in order to determine the automation/de-automation strategies by combining aspects of manufacturing systems such as costs, productivity, quality and flexibility. The sites studied in this research are the *Golf A5* assembly line at the mother plant in Wolfsburg, the *Touran* assembly line at the *Auto5000 GmbH* in Wolfsburg and the *Golf A5* assembly line in Uitenhage, South Africa. The aim of the analysis is to determine optimal levels of automation at the three production sites in order to make recommendations to automate or de-automate particular sections of the assembly processes.

II. THEORETICAL RATIONAL

A. Strategies and Automation

The study of Advanced Manufacturing Technologies (AMTs) and its relationship with business strategy receives much scholarly attention. It is widely recognized that AMTs are a major determinant of strategy and vice versa. An increasing number of researchers frequently posit that maximum benefit will accrue if there is a fit between AMTs employed by the firm [2]. In pursuing such a strategy, the emphasis is on efficiency and on the rigorous pursuit of cost reduction from all possible sources, which is regarded as a cost-leadership approach [2]. A low-cost strategy represents attempts by firms to generate a competitive advantage by becoming the lowest cost producer in an industry [3]. On the other hand, firms can pursue differentiation strategies that

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emphasise a chosen form of uniqueness that stems either from the product, process or service [4]. Differentiation strategies, in an automotive context, can relate to product design, manufacturing, logistics, marketing, IT etc. Typically manufacturing units serving a differentiation strategy tend to have more complex product lines and several discontinuities in the process side to facilitate greater product variety [5]. Hence, flexible manufacturing and assembly is an appropriate differentiation strategy in the automotive industry.

Many authors have argued that under certain industry conditions it is possible for firms to simultaneously pursue both cost-leadership and differentiation strategies orientations [6]. The implication is that pursuing a low-cost strategy requires the process side of manufacturing to be tightly integrated for effective cost minimisation [2]. Therefore, a combination of both strategies is appropriate in this case as the goals are to design cost efficient car assembly systems and to achieve high productivity, consistent quality and flexibility.

In order to compare different manufacturing technologies, based on the methodology proposed by Fraunhofer Institute, the final car assembly processes are classified according to the level of automation. The level of automation represents the portion of automated functions of a system in relation to the complete function of the system [7]. Each level of automation is associated with certain costs, which are explained below.

B. Manufacturing Costs

In manufacturing, the total cost per unit versus the level of automation can be represented graphically as shown in Fig. 2 [8]. As can be seen, the personnel costs decrease proportionally to the growing level of automation. At a beginning, economically justifiable operations are automated in the first place, therefore the automation cost increase almost linearly. Further on, the expenditure increases over-proportionally because of the rising complexity of the system. Hence, reaching complete automation causes the automation cost to increase exponentially while the personnel costs decrease only linearly, indicating a higher total cost. For the costs calculations, the relevant cost approach is used, where only the costs that make the largest contribution are taken into account [9].

The following cost types are necessary for the realisation of the assembly process:

- Personnel (all carrying out and planning activities in the assembly process; personnel costs consist of wages or rather salary and social costs; they essentially depend on personnel qualification)
- Operating material (installations for assembly and transport; operating material costs include all costs for running the operating material)
- Material (only consumables are relevant)
- Information

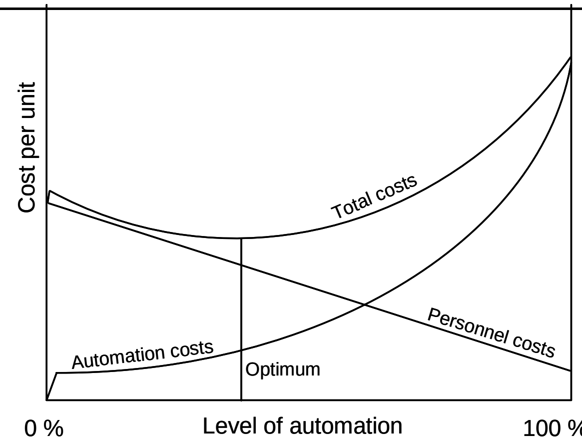

Figure 2: Graph of cost versus level of automation

C. Quality Indices

Quality is a top priority competition factor that should be integrated into all the processes of a company. Quality is characterised by the index system, which is defined as a compilation of quantitative variables, in which individual indices belong to each other, are supplementary to each other or explain each other in an objective and practical way. Thus, all these collected factors are focused on one common paramount target. An index is formed by the following elements: character of information, ability to quantify facts, and specific form of information [10]. All the information in the index should be adequately defined to avoid ambiguity.

For manufacturing and assembly processes, the quality standards are specified by the output quality indices, which are as follows:

- The quota of quality defects that does not meet the quality requirements in production immediately, i.e. the ratio of the defects to the whole production volume.
- The indices concerning the number of rejects and the rectification of rejects as well as their prevailing share of the whole production volume that shows the developing trend.
- The indices with regard to the individual/different types of defects in their relation to the total number of defects in the production.
- The indices referred to as customer complaints that are an indication of quality defects which have remained undiscovered in the production process.
- Audit-Notes, which are determined and assessed separately as indices by a company.

D. Productivity Indices

- The number of units that are planned to be built, the so-called scheduled number of units.
- The number of units that have actually been built.
- Times like the cycle times, manufacturing times, downtimes and total working times.
- Number of employees involved in the production process.

These are set in relation to:

- The availability of a production system with respect to the amount of standstill losses.

- The decreasing degree of performance with respect to loss of speed.
- The degree of quality depending on the number of parts which are produced with defects.
- The effectiveness of equipment as a whole with respect to the availability of production, the degree of performance and quality.
- Productivity which refers to the average number of vehicles built by one employee during a specified period of time and the number of vehicles built by all employees per hour.

'Soft' facts include:

- Flexibility to manufacture different units.
- The degree of complexity and its dependence on the different range of vehicle models compared to the basic model.
- Flexibility with regard to the possibility of producing many variations of a product on one line.
- The different range of vehicle models compared to the basic model.
- Flexibility with regard to the possibility of producing many variations of a product on one line.

All the cost, quality and productivity aspects are used for determining the best level of automation of the assembly processes at the three production sites as shown in the following section.

III. ANALYSES OF THE ASSEMBLY PROCESSES AT VW IN GERMANY AND SOUTH AFRICA

A. *Levels of Automation*

The analysis was done for the final assembly of the Golf A5 and Touran models in Germany and the Golf A5 model in South Africa. The assembly processes are done at the different level of automation giving a possibility of comparing and choosing the best automation strategy for the particular plant location.

The final assembly consists of the three main processes called Assembly Parts. Each Assembly Part in turn can be divided into Assembly Operations or Stations. Assembly Part 1 consists of five Assembly Stations and includes the following: roll forming of a *tailgate* and doors and a fitting of the cockpit. Assembly Part 2 also consists of five Assembly Stations and includes mainly a fitting of the power train and glasses. Assembly Part 3 includes seven Assembly Stations, which are typically fitting of trim panels, a cross member, a bumper, a complete front end, wheels and a battery.

To determine the level of automation, the Assembly Part is put in a matrix with Assembly Stations shown in columns and different manufacturing methods in rows according to the level of automation from the highest to the lowest (Table 1). The starting point of creating the levels of automation begins at the assembly of the Golf A5 model at Wolfsburg because this process is the most automated and therefore it is assigned the first level of automation

By de-automating one station at a time, the level of automation decreases. For example, Assembly Part 1 has five levels of automation because is consists of five Assembly Stations. The same is for Assembly Part 2, whereas Assembly Part 3 has seven levels of automation due to seven Assembly Stations. The last level of automation is the manual assembly, which is the way the Golf A5 model is assembled in Uitenhage. In between, there is one level of automation that represents how the Touran model is assembled in Germany, which is a combination of the automated and manual stations.

Table 1: Example of the Assembly Part 1 Matrix

Manufacturing operation / ***Level of automation***	***Roll forming tailgate***	***Fitting cockpit location brackets***	***Roll forming doors***	***Cleaning window flange, closing tailgate***	Priming window flange, opening bonnet
Level of automation 1 Golf A5, Germany	Automatic (1 Robot)	Automatic (2 facilities)	Automatic (4 Robots)	Automatic (3 Robots)	Automatic (3 Robots)
……………………… …..	………………… ...	……………...	……………….	……………………	………………
Level of automation 5 Golf A5, South Africa	Manual (hand rollforming device) t_M: 1,07 min	Manual t_M: 2,55 min	Manual (hand rollforming device) t_M: 2,4 min	Manual t_M: 2,81 min	Manual t_M: 2,81 min

For all the stations of the Assembly Parts, the cycle times and the number of personnel are determined based on the available information from the three production methods and their combinations. The results are matrices with different levels of automation and the number of necessary personnel for each station.

After establishing the matrices, the basis for the further analysis of each production site is created. Then the separate analyses of each production site can start.

B. *Manufacturing Costs*

If every created level of automation (in the matrices) is provided with costs, the result will be the representation of all relevant costs that are differentiated to resources depending on the different levels of automation. By adding up the different costs of all stations, the most economical solution and with it, the most economical level of automation of each matrix can be examined. The total unit cost for each level of automation in each Assembly Part is calculated for all the plant locations. of one of these tables is shown in Table 2.

Table 2: Example of the data for Assembly Part 1

Stations with parameters that are taken from Golf A5 Wolfsburg:								
Station	Workers in the line (direct)		QC workers		Re-worker		Auxiliary workers	
	t_{DW}, min	c_{DW}, €	t_{QC}, min	c_{QC}, €	t_{RW}, min	c_{RW}, €	t_{OW}, min	c_{OW} €
Fitting cockpit location brackets	0	0	0	0	1,127	0,10	0,748	0,57
Cleaning window flange, closing tailgate	0	0	0	0	0,127	0,10	0,748	0,57
Priming window flange, opening bonnet	0	0	0	0	0,127	0,10	0,748	0,57
Applying Cockpit glue	0	0	0	0	0,127	0,10	0,748	0,57
Cockpit fitting 1	0	0	0	0	0,127	0,10	0,748	0,57
Cockpit fitting 2	0	0	0	0	0,127	0,10	0,748	0,57
Removing Cable box, remaining screw connections	2,325	1,78	0,14	0,11	0	0	0	0
Remaining screw connections	0	0	0	0	0,127	0,10	0,748	0,57

The calculation for the roll forming *tailgate* station is carried out as an example. The total cost consists of the labour, investment, energy costs and overheads. The material costs are not included because they are considered the same for all production sites. All the costs are in €/unit.

The roll forming *tailgate* station is an automated station. Hence, no direct labour cost is calculated. For the supporting staff, the unit cost for the re-workers, $\mathbf{C_{RWj}}$, is calculated as follows:

$$\mathrm{C_{RWj}} = \frac{t_{RWj} \cdot c_{RW}}{t_{SH} \cdot d_W} \qquad (1)$$

where: t_{RWj} = manufacturing time of re-worker, min
C_{RW} = annual personnel cost for the prevailing worker, €
t_{SH} = shift duration in min,
d_W = number of working days.

The unit cost of auxiliary workers, $\mathbf{C_{OWj}}$, is calculated with the same formula using auxiliary worker time, t_{OW} and annual cost, c_{OW}:

$$\mathrm{C_{POWj}} = \frac{t_{OWj} \cdot c_{OW}}{t_{SH} \cdot d_W} \qquad (2)$$

To calculate the unit costs for the supervisors, first the number of supervisors, $\mathbf{n_{Mj}}$, for the chosen station has to be calculated (1 supervisor for 15 workers) as follows:

$$n_{Mj} = \frac{t_{DWj} + t_{QCj} + t_{RWj} + t_{OWj}}{15 \cdot t_C} \qquad (3)$$

where: t_{DWj}, t_{QCj}, t_{RWj}, *and* t_{OW} are manufacturing times of direct, quality control, re-worker and auxiliary workers accordingly in min,
t_C = cycle time, min.

After that the personnel costs per unit for the supervisor, $\mathbf{C_{PMj}}$, can be calculated with the following formula:

$$\mathrm{C_{PMj}} = n_{Mj} \cdot \frac{n_S \cdot c_{PM}}{n} \qquad (4)$$

where: n_S = number of shifts per day,
c_{PM} = annual personnel cost for master, €,
n = number of units per day.

Before calculating the other personnel costs per unit, it is necessary to determine the investment (capital) costs per unit, $\mathbf{C_{INVj}}$:

$$\mathrm{C_{INVj}} = \frac{T_{INVj}}{a \cdot n_{an}} \qquad (5)$$

where: T_{INVj} = total investment costs, €,
a = period of depreciation, years.
n_{an} = annual number of units.

Then, the personnel costs for maintenance per unit $\mathbf{C_{PMAi}}$, can be calculated, which is taken as 50% of the investment costs per unit. The planning personnel cost per unit, $\mathbf{C_{PPj}}$, is 7% of the investment costs per unit.

The personnel cost for industrial engineering per unit, $\mathbf{C_{PIEj}}$, is calculated with the following formula:

$$C_{PIEj} = \frac{\sum t_{Mj}}{2} \cdot \frac{d_{WW} \cdot c_{PIE}}{d_W} \cdot \frac{1}{a \cdot n} \qquad (6)$$

where: t_{Mj} = manufacturing time for the prevailing worker, min/unit,
d_{WW} = number of working days per week,
c_{PIE} = annual personnel cost for Industrial Engineering employee, €.

The total personnel cost per unit is multiplied by a factor 1.11 to include the labour overhead costs.

The energy cost per unit, $\mathbf{C_{Ej}}$, is calculated as follows:

$$C_{Ej} = \frac{P_{Ej} \cdot C_{POW}}{n} + \frac{P_{Ej} \cdot C_W \cdot t_C}{60} \qquad (7)$$

where: P_{Ej} = power for station j, kW
C_{POW} = energy cost rate for power, €/kW
C_W = energy cost rate for work, €/kWh

The equipment cost per unit, $\mathbf{c_{EQj}}$, is determined as follows:

$$C_{EQj} = \frac{1}{n} \cdot \frac{T_{INVj}}{T_{INVWOB}} \cdot T_{EQWOB} \tag{8}$$

where: T_{INVWOB} = total investment costs for all Assembly Parts for Golf A5 Wolfsburg, €,
T_{EQWOB} = total equipment costs for all Assembly Parts for Golf A5 Wolfsburg, €.

The additional operating expenses, $\mathbf{C_{Ej}}$, are calculated as follows:

$$C_{Ej} = \frac{P_{OSj} \cdot C_{POW}}{n} + \frac{P_{OSj} \cdot C_{W.} \cdot t_C}{60} \tag{9}$$

where: P_{OSj} = power to produce compressed air, kW,
C_{POW} = energy cost rate for power, €/kW,
$C_{W.}$ = energy cost rate for work, €/kWh

By adding up all the total unit costs of each Assembly Station and the total unit cost of the whole Assembly Part for a specified level of automation are determined for each production site. Due to differences in labour and running costs, each production site will have different total costs for the same Assembly Part. The total costs for the Golf A5 model produced in Germany are shown in Table 3 with the present level outlined in bold, while the optimal level is shown in bold and shaded.

Table 3: Unit costs of the assembly of the Golf A5 model produced in Germany

Level of Automation	Assembly Part 1, €	Assembly Part 2, €	Assembly Part 3, €
1	**1,00**	**1,20**	**1,20**
2	1,10	1,30	1,10
3	1,20	1,10	1,10
4	1,30	**1,00**	**1,00**
5	1,40	1,40	1,30
6			1,40
7			1,50

As can be seen for Assembly Part 1, the first level of automation is the optimal level of automation because this level has the lowest costs. This level also predominates in practice. Therefore Assembly Part 1 is designed optimally. The workers and the investment costs cause the highest share of the total costs per unit. The cockpit fitment is the most expensive station in this Assembly Part. With a decreasing level of automation, the other workers and investment costs take a smaller and smaller part but costs for direct workers in the line increase accordingly. This is the main reason why even the second level of automation is already more expensive than the first one. The other types of cost only take a small part of the total costs per unit.

In Assembly Part 2, the fourth level of automation is optimal. The costs of workers in the line increase, whereas, on the other hand, the costs for all the other workers as well as investment in equipment do not increase in the same way. Thus, in order to reach the optimal level of automation, the stations stamping vehicle identity numbers, fitting the gearshift, closing the bonnet and fitting all the windows have to work in the same way as in the assembly line of the Auto5000 GmbH.

In Assembly Part 3, the fourth level of automation is also optimal. On the first level, the investment costs cause the highest part of the total costs per unit, followed by the personnel costs for maintenance, re-workers and other workers. As in Assembly Part 2, the costs for workers in the line increase with decreasing automation, while costs for re-workers, other workers and maintenance decrease until the cost optimum is reached in level 4. After that the costs for workers in the line increase accordingly, which makes every further de-automation uneconomical. In order to put level 4 as an optimal level of automation into practice, the stations opening the bonnet, putting in and fitting the CW trim panel, putting in and fitting the battery, fitting the cross member as well as the rear bumper have to be designed as in the Auto5000 GmbH. The total costs per unit of the production site of the Auto5000 GmbH are shown in Table 4.

Table 4: Unit costs of the assembly the Touran model produced in Germany

Level of Automation	Assembly Part 1, €	Assembly Part 2, €	Assembly Part 3, €
1	1,30	1,20	1,30
2	1,20	1,30	1,20
3	**1,00**	1,10	1,10
4	**1,10**	**1,00**	**1,00**
5	1,40	1,40	1,40
6			**1,50**
7			1,60

As can be seen, for Assembly Part 1, the third level of automation is optimal (marked red). At this level, the highest costs per unit are the workers on the line, followed by the investment costs. But in practice, the actual automation level is level 4 (dotted fields). To reach the optimal level, the stations fitting cockpit location brackets and cockpit fitting 1 and 2 have to be designed fully automatically as it is done on the Golf A5 model assembly line.

In Assembly Part 2, the fourth level of automation is the optimal level. This level also predominates in practice. Therefore, Assembly Part 2 is designed optimally. The most expensive station of this Assembly Part is fitting the complete power train combined with all under bodywork.

In Assembly Part 3, the fourth level of automation also represents the optimum but in practice level 6 predominates, which again requires a higher level of automation in the assembly line of the Touran model at the Auto5000 GmbH. On level 6, the fitting of the front end is the most expensive station because of the high personnel costs for workers in the line. The second most expensive station is the pre-mounting and fitting of wheels. Both of the stations have high investment costs as well. Therefore, both of these stations and the station placing the spare wheel in the boot have to work fully automatically as it is done in the Golf A5 model assembly line at the same location.

For the Golf A5 model produced in South Africa (Table 5), most of the manual levels of automation reach the optimal level, and this is also done in practice at the moment. Therefore, in this step of the analysis, no changes of stations or other operations are necessary.

Table 5: Unit costs of the assembly of the Golf A5 model produced in South Africa

Level of Automation	Assembly Part 1, €	Assembly Part 2, €	Assembly Part 3, €
1	1,40	1,40	1,60
2	1,30	1,30	1,50
3	1,20	1,20	1,30
4	1,10	1,10	1,20
5	**1,00**	**1,00**	1,10
6			1,40
7			**1,00**

In Assembly Part 1, the most expensive station is fitting the cockpit. It takes nearly half of the total costs per unit. In Assembly Part 2, fitting the power train combined with the whole under bodywork takes the highest costs per unit, which is even more than the half of all total costs per unit. In Assembly Part 3, pre-mounting and fitting wheels show the highest part of the total cost. It is possible that the costs can be reduced further by reducing the level of automation at the production site in South Africa. However, there are no data available about manufacturing times and costs for facilities with even less automation. Also, further de-automation could lead to lower quality.

C. *Quality*

The quality indices for the three production sites are put in one table as shown in Table 6. These include Field data, Audit data of vehicle and process, Vehicle Preparation Centre (VPC) data and Direct Runner Rates (DRR). Field data show the quality of vehicles from a customer's point of view with the recordings of trouble cases per vehicle. Vehicle auditing is an element of the Quality Assurance System, which judges the effectiveness of the Quality Management System on the basis of quality delivered in a snapshot. The Vehicle Preparation Centre, located in Japan, records defects in vehicles delivered from Wolfsburg and Uitenhage in a 100% control. DRR is an index by which each plant is measured and it indicates the percentage of vehicles, which pass the quality check after the assembly process (CP7) and at the final checkpoint (CP8) after the water and road tests. The effectiveness of the Quality Management Systems is judged by the Process Audits expressed as a percentage.

Table 6: Quality indices

Plant	Trouble cases per unit			Field Data (Trouble cases per unit)	Audit Points (Target)	VPC Data (Trouble cases per unit)	DRR CP7/CP8, %	Process Audit, %
	Assembly Part 1	Assembly Part 2	Assembly Part 3					
Main Plant in Wolfsburg	0,01345	0,02796	0,00465	0,05432	80(90)	2,44	58/62	94
Auto5000 in Wolfsburg	0,03872	0,01235	0,01987	0,01076	82(90)	0,87	69/95	91
Plant in South Africa	0,10984	0,03561	0,96543	0,02345	92(90)	2,23	81/89	92

The next step is the investigation into finding the optimal level of automation regarding quality. All other quality factors can only be concluded from these results, because the data are assigned to the whole examined assembly area. All the above quality indices values are assessed as follows:

- The ranking of all values in comparison to each other (best, second best and worst) is done.
- Allocation of points to each status:
  The best gets 3 points, the second best gets 2 points and the worst gets 1 point.
- Attach importance to each value:
  The most convincing values are the assembly Trouble Cases (TC); they get the highest weight and are multiplied by the factor 3.
  All the other values go down in assessment in single weight.
- Total sum of all points: The best existing level of automation has the most points.

The results of the analysis showed that the Auto5000 Wolfsburg manufactures best according to all the quality indices. The second part of the task is to find the theoretical optimal automation. Therefore each Assembly Part, which delivers the fewest trouble cases per vehicle, is investigated. These collected data are summarized in one theoretical optimal level of automation.

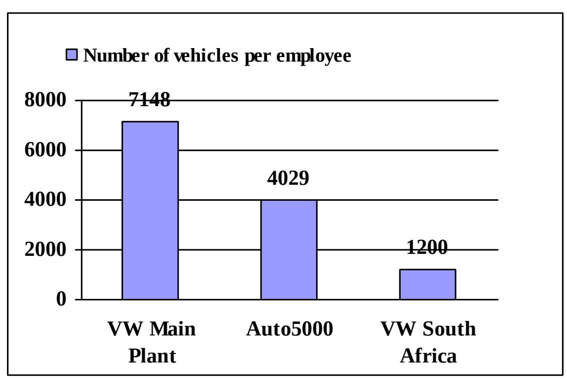

Figure 3: Annual vehicle quantities per employee

D. Productivity and Flexibility

On the basis of the above described matrices, the productivity figures are examined in relation to the number of workers. These workers are later seen in relation to the vehicles built and the time needed for that. These relations are the indices of productivity taken into consideration in this analysis. The result of this analysis confirms that a highly automated way of manufacturing is also highly productive when taking into account that the smallest number of employees produces the highest number of vehicles as can be seen from the comparison shown in Figure 3. On the other hand, the calculation of effectiveness shows that the availability of the high-automated production is susceptible to faults and trouble cases because of its complexity. On account of this, a high number of faultless units can be reached, besides other methods, when produced at a lower automated level, which includes the integration of highly skilled employees.

Flexibility of production equipment is too difficult to quantify in financial terms. Also product variations can not be considered in this case since the automotive production equipment is specifically designed for a range of vehicle models. Nevertheless, the production equipment should have a sufficient capacity to accommodate a limited increase in production quantities. Therefore, in determining the levels of flexibility of Assembly Parts, the focus is on two aspects:

- variations of production quantities and;
- a number of workers required.

From this point of view, the most flexible is the production system that has to change the least to cope with the increase/decrease of production quantities, i.e. a minimum variation in the number of workers. The results of the analysis for a ±20% variation of production quantities are shown in Table 7. The bold and shaded fields show the most flexible production system with little or no variation in the number of workers, while the underlined fields represent the least flexible production systems with a large variation in the number of workers needed to accommodate different production quantities. From these data, the optimal levels of automation are chosen with regard to flexibility. As can be seen in Table 7, more than one optimal level of automation exists for all the assembly processes except for Assembly Part 1 at the VW main plant.

Table 7: Optimal Levels of automation with regard to productivity and flexibility

Golf A5 Wolfsburg																	
	Number of workers																
	Assembly Part 1					**Assembly Part 2**					**Assembly Part 3**						
Level / Units	**1**	2	3	4	5	**1**	**2**	3	4	5	**1**	2	3	**4**	5	6	7
-20%	**8**	10	14	19	19	**7**	**10**	10	9	34	**6**	6	8	**8**	13	15	18
Actual	**9**	11	14	19	22	**8**	**10**	11	12	42	**6**	8	8	**8**	13	17	20
+20%	**10**	13	18	25	28	**9**	**12**	14	14	48	**6**	8	10	**8**	14	18	23
Auto 5000 Wolfsburg																	
Level / Units	**1**	**2**	3	4	5	1	**2**	**3**	4	5	**1**	2	**3**	**4**	5	6	7
-20%	**8**	**10**	13	18	18	7	**10**	**10**	9	32	**6**	6	**8**	**8**	12	15	18
Actual	**9**	**11**	14	19	21	8	**10**	**10**	10	39	**6**	8	**8**	**8**	13	17	20
+20%	**10**	**12**	15	23	25	9	**11**	**11**	11	45	**6**	8	**8**	**8**	14	18	23
Golf A5 SA																	
Level / Units	1	**2**	**3**	**4**	5	**1**	**2**	**3**	**4**	5	**1**	**2**	**3**	**4**	**5**	**6**	7
-20%	4	**6**	**8**	**10**	8	**4**	**6**	**8**	**7**	11	**4**	**5**	**7**	**7**	**9**	**9**	9
Actual	5	**6**	**8**	**10**	9	**4**	**6**	**8**	**7**	12	**4**	**5**	**7**	**7**	**9**	**9**	9
+20%	5	**6**	**8**	**10**	9	**4**	**6**	**8**	**7**	14	**4**	**5**	**7**	**7**	**9**	**9**	10

IV. RESULTS AND DISCUSSION

The levels of automation of the assembly processes with regard to the three main aspects such as costs, quality and quantity are compared to obtain the optimal levels for each production site. If the different optima correspond with each other, the total optimum for the individual Assembly Part is already found. Otherwise, if the optima show differences in a certain Assembly Part, a further examination has to be carried out. In the combination of the optima, the optimal levels of costs are defined as the basis. Both of the other aspects are compared with the optimal level of costs to find a total solution for each production site. The results are shown in Table 8.

A Production of the Golf A5 model in Wolfsburg

For Assembly Part 1, level 1 is the optimal of automation level from a cost point of view, which represents actual assembling in practice. The productivity indices show the same optimum. But the differences between the optimal level of costs and quality have to be remedied. The difference between the first and the third level of automation from a quality point of view is 0.005 trouble cases per vehicle. A more detailed examination of the operations with regard to quality aspects revealed that the assembly stations of roll forming *tailgate* as well as roll forming of *doors* cause this difference. This is attributed to the robotic station, which allows only a very small tolerance for assembling. If this tolerance margin is not kept, the robot is not able to react appropriately, because an automatic station is not flexible enough to compensate abrupt variances of tolerances. In order to achieve a better quality, an improvement of the adjustment of the robot, a more appropriate maintenance of the robot or a further development of the roll forming tool for robots should be investigated.

Table 8: Optimal levels of automation

Index	*Golf A5 Wolfsburg*			*Touran at Auto5000 Wolfsburg*			*Golf A5* **Uitenhage**		
	Optimal Level of Automation of Assembly Parts								
	AP1	AP2	AP3	AP1	AP2	AP3	AP1	AP2	AP 3
Cost	1	4	4	3	4	4	5	5	7
Quality	3	4	4	3	4	1	3	4	1
Productivity/Flexibility	1	2	4	2	3	4	4	4	6
Present Automation Level	1	1	1	4	4	4	5	5	7
Recommended Automation Level	**1**	**4**	**4**	**3**	**4**	**3**	**5**	**5**	**7**

For Assembly Part 2, the determination of the mal level of costs and quality deliver the same level of automation as the optimal, which is level 4. However, the actual level of automation is level 1 and in productivity aspects, the levels 1 and 2 demonstrate the best options. But level 4 shows a rising productivity compared to a decreasing number of units. And, additionally, it provides a better flexibility because the operations are done manually and can be modified easily. Therefore, the actual level of automation in Assembly Part 2 has to be de-automated to reach the total optimal level but the improvement of the quantity indices have to be considered.

For Assembly Part 3, the results of costs, quality and productivity are also the same, which is level 4, whereas the actual level of automation is 1 indicating that a lower automation level is preferred for this operation.

B Production of the Touran model at Auto5000 GmbH in Wolfsburg

For Assembly Part 1, level 3 is the optimal level with regard to costs and also to quality, whereas the actual level of automation is level 4 in the Auto5000 GmbH. Regarding flexibility and productivity, level 2 is the optimal level. Since the cost and quality indices point to the lower lever of automation, Level 3 is recommended for Assembly Part 1.

As for Assembly Part 1, the optimal levels of automation regarding cost and quality correspond to each other for Assembly Part 2 as well. But, for this Assembly Part, level 4 represents the actual level of automation. Although the productivity/flexibility index points to higher automation (level 3), it is recommended to keep the present method of production, therefore the Assembly Part 2 is optimally designed.

For Assembly Part 3, the results of costs (level 4) and quality (level 1) do not correspond, which is the main concern. It appears that even with the highly extensive training programme, which takes place at the Auto5000 plant, the consistent quality is not possible without automation for this assembly process. Concerning productivity, levels 3 or 4 can be the optimum. Based on the results, Assembly Part 3 should be automated to level 3 to improve quality.

C. Production of the Golf A5 model in Uitenhage

For the production site in Uitenhage, all the Assembly Parts have similar discrepancies for all the indices. The quality index points to a higher level of automation, while the cost and productivity indices show that the present methods are the most economical. The above-mentioned argument that manual assembly is as good in terms of quality as automatic assembly or even better is not valid for the manufacturer in Uitenhage. For example, comparing the assembly of roll forming *tailgate* and *doors* in Uitenhage and at the Auto5000 GmbH shows that 0.101 more trouble cases per vehicle is recorded in Uitenhage. The reasons behind poor quality of manual operations will have to be investigated. In this study, it is assumed that quality can be raised to the similar levels as at the other production sites. Therefore, it is recommended not to change the levels of automation of the Assembly Parts but to investigate and improve quality.

SUMMARY

In this research, the assembly lines of three different production sites of VW AG, the Golf A5 assembly line in Wolfsburg, the Touran assembly line in the Auto 5000 GmbH in Wolfsburg and the Golf A5 assembly line in South Africa, were analysed to find the optimal level of automation in order to recommend the best automation strategy with regard to a production site. The methodology is based on obtaining the optima for the costs, quality, productivity and flexibility indices by examining all possible production methods. The optima are, then, compared and if found to be the same, the production process is considered as optimally designed. If the optima do not correspond, the necessary adjustments are made to find the best solution. This approach combines all the major factors of the production system and product quality in order to achieve a good balance in designing and optimising manufacturing processes. Although the cost optimum is the basis of the analysis, other factors such as quality and flexibility also play an important role in decision-making.

The results of the study of the Golf A5 assembly line in Wolfsburg illustrate that the examined Assembly Parts 2 and 3 have to be de-automated to achieve the optimal level of automation. Assembly Part 1 is optimally designed, however, a quality improvement is required. The actual level of automation in Assembly Part 2 has to be de-automated to reach the total optimal level but the improvement of the quantity indices have to be considered. In Assembly Part 3, the actual level of automation has to be de-automated to reach the optimal level as well. Also the quality as well as the modifications in quantity should be kept in mind.

The examined Assembly Parts in the production site of the Auto5000 GmbH in Wolfsburg have to be automated according to the obtained results. This conclusion is valid for Assembly Parts 1 and 3, which have to be automated from the actual levels of automation to reach an optimal level. The necessary variations in quantity have to be considered in both parts. Additionally in Assembly Part 3 the quality improvements are needed. The actual level of automation in Assembly Part 2 represents the total optimal level of automation with regard to all indices. Hence, this process is already optimally designed.

The actual levels of automation in the Golf A5 assembly line in Uitenhage are optimally designed according to the obtained results. However, especially from the point of view of quality, the processes have to be improved. The manufacture of the Auto5000 GmbH illustrates that a manual assembly with high quality is possible in practice. So, the manufacture in Uitenhage has to be adapted in order to produce a better quality in the actual and optimal level of automation.

This technique is valuable for decision-making on the best automation strategy for new systems or for optimising existing production systems with regard to automation/de-automation without compromising the high quality of products. The analysis is based on prior information of similar production systems with respect to cost and productivity. Some assumptions in terms of quality would be needed in case of introduction of new processes.

The case study demonstrated that fully automated as well as completely manual processes are not the optimal in automotive assembly. It was also shown that the fictitiously determined levels of automation consisting of automated and manual stations is a better option if the combined effects of cost, quality and flexibility are considered. This means that both long term vision and logical procedures are as important as the efficient design of the assembly lines to guarantee an efficient manufacturing process.

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REFERENCES

[1] Lay, G., Schirrmeister, E., 2001. Sackgasse Hochautomatisierung? PI-Mitteilung. N 22, ISI, Fraunhofer

[2] Kotha, S., Swamidass, P. M., 2000. Strategy, advanced manufacturing technology and empirical evidence from U.S. manufacturing. Journal of Operations Management, 18, pp. 257–277.

[3] Porter, M., 1980 Porter, M.E., 1980. Competitive Strategy: Techniques for Analyzing Industries and Competitors. The Free Press, New York.

[4] Mintzberg, H., 1988. Generic strategies: toward a comprehensive framework. In: Advances in Strategic Management, Vol. 5. JAI Press, Greenwich, CT.

[5] Kotha, S., Orne, D., 1989. Generic manufacturing strategies: a conceptual synthesis. Strategic Management Journal 10 3 , pp 211–231.

[6] Hill, C., 1988. Differentiation versus low cost or differentiation and low cost: a contingency framework. Academy of Management Review 13, pp 401–412.

[7] Fichtmüller, N., 1996, Rationalisierung durch flexible, hybride Montagesysteme, Heidelberg.

[8] Hartmann, M. 1993, Entwicklung eines Kostenmodells für die Montage – Ein Hilfsmittel zur Montageanlagenplanung, Aachen.

[9] Ross, P., 2002, Bestimmung des wirtschaftlichen Automatisierungsgrades von Montage-Prozessen in der frühen Phase der Montageplanung, p.

[10] Tomys, A.K., 1995, Kostenorientiertes Qualitätsmanagement, Qualitätscontrolling zur ständigen Verbesserung der Unternehmensprozesse, Munich.

[11] Heinen, E., 1978, Industriebetriebslehre: Entscheidungen im Industriebetrieb, Gabler, p. 147.