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SELECTION OF THE MOST SUITABLE MATERIAL HANDLING SYSTEM IN PRODUCTION

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Abstract
When building a new company or optimising an existing one, material handling (MH) is often forgotten. Therefore, the paper presents a decision tree, on the basis of which it is possible to select the most suitable MH system by simulation depending on the selected production parameters. Such a simulation can greatly facilitate the selection of the most suitable MH system which will ensure minimal time consumption and still acceptable costs.

To perform the simulation, a generalised production system model for 5 different MH systems was created in the FlexSim software, with which 32 different scenarios could be simulated depending on the selected production parameters, tested in a production facility of injection moulded components for the automotive industry. The data obtained from the simulations were then used to analyse the influence of the selected parameters on possible MH systems. For all potential scenarios, the solutions of which are acceptable for MH, a cost-benefit analysis was performed. Based on the analysis, a difference of 75 % between the most and least favourable scenarios was established.
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Key Words: Production, Material Handling Systems, Simulation, Optimisation, Cost-Benefit Analysis

1. INTRODUCTION

Material handling systems are an important element in the operation of a production plant. In the planning of new production plants or in the optimisation of existing ones [1], less attention is paid to the selection of MH than to the equipment allocation and its efficiency. As MH serves as a support function to production, the shortcomings of MH are manifested indirectly, such as delays in delivery times, low equipment (WE) efficiency, and longer production pace. As early as the 1980s, Toyota developed the concept of lean production, which emphasises the principles of just-in-time (JIT) and the smallest possible extent of intermediate stocks "work-in-process" (WIP) [2]. The concept of lean production has become the standard in modern production, where MH has one of the main roles in its operation.

Early methods for selecting the most appropriate MH were checklists and mathematical programming [3]. With the advancement of computer technology, systems such as SEHM (Selection of Equipment for Material Handling) and MATHES (Material Handling Equipment Selection) [4, 5] have emerged, combining databases, knowledge bases, and inference algorithms. These systems take into account many parameters in production, which are entered into the software which generates the most appropriate MH. It would also be reasonable to consider MH for bottlenecks [6], as they should have the priority, and the optimal path algorithm [7]. These methods focus on unit loads (UL) to be transported and on the layout of working equipment in a production facility, but do not address the issue of improving those elements in production. As building land is expensive, multi-storey production plants are often erected, which entails a problem of transporting unit loads between storeys. The purpose of this paper is to show that, with the help of computer simulation of the influence of various production parameters and performed cost-benefit analysis, it is possible to find the most suitable MH selection in production.

2. LITERATURE REVIEW

MH means to provide the right material in the right condition, delivered to the right place in the right position and sequence, for the right price and with the right method [8]. All the above criteria must be considered when selecting the most suitable MH. When transferring material, it is first necessary to define the unit load [9] that MH will handle. Depending on the unit load, it is necessary to select suitable material handling equipment (MHE) that can handle it. According to the possibility of movement, MHE is divided into: 1) fixed route of operation, 2) fixed space of operation and 3) free movement [10]. Different technologies can be used in each of these options. The simplest MH is a "forklift approach" where a means of transport picks up a UL and delivers it to the destination and then heads for the next UL. In large production facilities, the "milk-run" concept, established by Toyota in its lean production, is common. A "milk-run" train circulates on a fixed route, picks up and places ULs as needed. A simulation with automated inductively guided vehicle, automated rail-guided vehicle and automated conveyor system was studied by [11]. The simulation showed that the highest productivity of the system is achieved when using automatic conveyor belts as a transport means, but it has the worse flexibility. There are several ways to plan routes, trigger orders and levels of automation [12]. As the level of digitalisation of production increases, automated guided vehicles (AGVs) are increasingly implemented, operating at different levels of autonomy [13] and can be controlled on the basis of fuzzy logic and optimized by a generic algorithm otherwise used for large AGV systems [14]. AGVs can operate as a "forklift-approach" or "milk-run" concept. One of the most common MHs in logistics is transporters, but they are less common in production due to their poor flexibility. There are different types of work equipment layouts (WEL) for different types of products [15]. When planning WELs in production, MH is often only taken into account towards the end, despite the fact that their functionalities are closely related. In production facilities facing a lack of space, "dead ends" may occur, which is an obstacle to MH. In the paper [16], the authors showed that order picking costs can vary up to 50 % depending on the more or less optimal selection of commissioning method.

In a production environment, simulation can be defined as a computer method that mimics the operation of a real production system in a significantly shorter time [17]. The simulation allows us to reduce uncertainty in decision-making because it can be used to explore different solutions with a relatively low cost compared to testing these options in reality [18]. The simplest method of simulation is the "Monte Carlo" simulation. Random samples from statistical distributions are combined, for example added or multiplied to obtain some probability of a common event. If these random phenomena are shown as random events that occur over a period of time, a system of discrete events is obtained. Based on such a method, plenty of commercial software is available to simulate production, such as Plant Simulation, Arena, Simio and FlexSim.

When selecting to purchase new equipment, it is always necessary to take into account the cost of purchase and subsequent operation, which represents the Total Cost of Ownership, TCO [19]. In addition to the costs, it is also important what benefits the equipment will bring. The cost-benefit analysis (CBA) is a systematic approach to assessing the strengths and weaknesses of alternatives that meet the requirements of an investment alternative. This is a technique used to determine the alternative that is the most advantageous in terms of benefits and costs. Depending on the type of data they cover, two different implementations are possible: money-based CBA and value-based CBA. A value-based CBA is used when the benefit cannot be directly evaluated in monetary terms. For the transformation into a utility factor, the values of each criterion need to be adjusted with rating scales [20].

3. METHODOLOGY

3.1 Real production facility as a starting system

A real-case study of WEL and the material flow of a polymer injection moulding plant was carried out to obtain the results which would be a realistic reflection of the production, the related problems and parameters. From the material handling point of view, it provides a good representation of the conditions that can occur in any production. Each polymer injection moulding machine has its own material inlet and outlet. One of the input material flows is in the form of a granulated polymer which is vacuum-transported to the machine via a tube. This is a special form of a transporter that is very frequently used in the polymer transformation industry. The transport of this material will not be included in the analyses, as this material flow is not representative for determining the transport system for general production systems due to the required drying and many different types of granulate. Another input material flow is empty packaging in the form of cardboard boxes, plastic crates, pallets or other similar containers for collecting manufactured injection moulded products into full unit loads. The source of packaging is an intermediate storage warehouse in production, while it reaches this warehouse from the packaging warehouse (logistics). Packaging full of products or full unit loads represent the material output flow from the machines. Full packages are stacked on pallets which are then transported to the product warehouse (logistics).

An average material flow density of unit loads (Table I) for three work shifts was extracted from work orders. The material flows were classified as to whether they include pallets or not. In the case of pallet material flow, a pallet full of boxes is to be transported to the logistics. In a pallet-free system, however, full boxes are not bundled and must be transported to logistics individually.

Table I: Average material flow density of unit loads.

Unit load type	Material flow of pallets	Material flow of boxes
Full unit load	1.54 UL/h	31.95 UL/h
Packaging	9.88 UL/h	8.33 UL/h

3.2 Simulation and simulation scenarios

The FlexSim software was used for simulation. This software already has a library of elements for simulating production. A simplified factory layout was input into the software environment and the triggering of transport orders was entered based on the previously mentioned work orders. Once a transport order is triggered, it is included in the list of orders used by MH for the distribution of tasks. The simulation includes waiting and transport times of ULs, the average amount of LUs in circulation, the occupancy of vehicles with operations as % of operating time and the length of completed routes of means of transport.

We decided to simulate 5 different MHs: forklift approach, milk-run system, AGV system, system of transporters and rack system with AGV. The following limitations were taken into account in the simulation: in the forklift approach, the transport can also be done manually with trolleys provided that the permitted walking distance per work shift is limited to 15 km. If this limitation was exceeded or if the operation was too slow, appropriate motorized means of transport were added. When the means of transport is a forklift, the forklift first picks up the nearest UL from the list, which has waited the longest to be transported. In the "milk-run" system, route planning and stopping at a work equipment (WE) were optimised first. Based on the optimisation results, we chose a variable route and stopping at each machine instead of stopping in zones. To reduce complexity, a human operator was used. In the case of a goods lift, the maximum number of trailers is 1. For AGV systems, a dedicated software tool offered by FlexSim was used. It works on the principle of checking the ULs to be transported along a certain detour route. The AGV starts the detour when a unit to be transported appears in the list. The distribution of checkpoints in the detour was optimised. The system of transporters works with two separate systems for a two-way flow from a WE to logistics and vice versa, which are placed one above the other. If operators are present at a WE, the system of transporters for material flow into production is shortened, as this reduces the required level of automation of the system of transporters.

A non-standard MH was also examined, where cooperation between operators and AGV vehicles occurs by way of racks in the zones. The operator loads full pieces on the rack that is transported by the AGV to the logistics, where a person in charge of logistics unloads it and loads the necessary packaging. The AGV then takes the rack back to the logistics, where the operators carry the packaging to the associated machines. So, a smaller number of AGVs is needed that periodically exchange racks between production and logistics. The waiting of the AGV vehicle was optimized – the vehicle, after having dropped off the rack, goes fetch a rack of the next zone, while the rack of the previous zone is unloaded and loaded with packaging.

One of the two main factors monitored in our analysis of the different scenarios were the parameters in production that have impact on MH. The parameters were selected depending on the assumed severity of their impact on MH and depending on how often they occur in production. The described problems were observed in several Slovene production companies, which was, in fact, the motive for this research. There is a plethora of parameters that affect the suitability of MH selection, but only 5 parameters were selected due to the exponential increase in the number of required simulations: unit load form, arrangement of transport routes, presence of an intermediate storage warehouse, need for a lift and presence of operators at work equipment.

In total, this is 32 scenarios, and up to 5 MHs need to be simulated for each of them, if they can be set up. Boxes/containers and pallets were chosen as the unit load form. In most productions, the material is transported on pallets. Due to the JIT philosophy, however, modern productions tend to choose boxes as unit loads within production, thus minimizing the average amount of circulating unit loads (WIP). This parameter was selected to highlight the problems represented by different material flow densities and different dimensions of unit loads. In production, circular routes are not always available around all WEs or points where material is collected and deposited. This parameter will be used to examine the impact of dead ends on MH and what limitations occur in such a WEL. This parameter was further selected because of its strong impact on the possibility of setting up a milk-run system. As already mentioned in the literature review, intermediate storage warehouses reduce the need for material handling, but occupy space that could be used for WEs. This parameter will be used to assess what benefits intermediate storage warehouses bring and how their elimination affects an individual MH. When looking at Slovene production companies, it has been noticed that many companies decide to have production on several storeys due to cost savings in the purchase of land. The problem is not only the waiting time while traveling with the lift, but also congestions that occur in the event that the lift needs more means of transport at the same time. This parameter will be used to analyse the actual obstacle that the use of a lift presents in the material flow and how the introduction of a lift limits our selection of MHs. The presence of operators will not be simulated in the scenarios, yet it has impact on the possibility of introducing certain MHs and thus reduces the number of required simulation scenarios. In case the operator is not present at a WE, automated systems need to be introduced that will load ULs on autonomous MHEs, such as systems of transporters and AGV.

3.3 CBA model

For each scenario, the results will be observed for work in one shift, in two shifts and in three shifts. We opted for this division because it has a strong impact on the payback period of purchased assets. Despite the fact that the observed production is performed in three shifts, we want to show the justification of the investment in production material handling systems under different conditions. All goals and values were determined in a team consisting of experts at the faculty and employees from the production company under consideration. As a narrower scope of a benefit analysis was needed, a small number of goals was selected, the values of which can be determined by simulation results and by reviewing the theory. The following goals have been selected: lowest possible variability of transport times, smallest possible average quantity of unit loads in circulation, highest possible MH flexibility and narrowest possible width of MH transport routes.

The goals were classified by importance through teamwork and the appropriate LU weight or importance factor was assigned to them using the method of improved individual comparison of criteria (Table II). The weights were then normalised to represent a total of 100 %.

Table II: Rank of criteria and associated weights.

Rank	Criterion	Weight	Customised weight	Normalised weight
1	MH flexibility	1	1	0.38
2	Transport time variability	0.85	0.85	0.33
3	Average quantity of ULs in circulation	0.6	0.51	0.20
4	Width of MH transport routes	0.45	0.23	0.09

A cardinal scale 0 to 5 was used to calculate benefit estimates and the degree of fulfilment *DF*. The benefit contribution BC_{ij} of the j^{th} target criterion and the j^{th} alternative is obtained by Eq. (1), where W_i represents the weight of the i^{th} goal or criterion, while DF_{ij} represents the degree of fulfilment of the i^{th} goal or criterion, the j^{th} alternative. The variability of transport times was obtained by calculating the standard deviation of transport times of unit loads in an individual scenario. The variability of transport times should be as low as possible. To calculate the benefit score, a value function was used, in which score 0 represents the global maximum of variability in all scenarios and score 5 represents the global minimum of variation. The value function is presented in Eq. (2), where *DF* represents the degree of fulfilment/benefit score, and *Var* represents the variability of transport times. The indices *max* and *min* represent the global minimum and maximum of variation. The average quantity of ULs in circulation represents *WIP* and it should be as low as possible. As with the variability of transport times, a value function, Eq. (3), was used for the average quantity of ULs in circulation, except that *WIP* represents the average quantity of unit loads in circulation. The larger the width of the transport routes, the less surface in production remains for WEs, so the needed width of the transport routes should be as small as possible. Again, a similar value function, Eq. (4), was used, where *TR* represents the width of transport routes, ranging between 1.5 and 3.5 m depending on the selected means of transport. Since the data for global maxima and minima were obtained from the theory, the final form of the equation is given here. For the MH flexibility, a rating table was used that adjusts a descriptive characteristic to a numerical one, where 0 represents a completely inflexible system and 5 represents a completely flexible system (Table III).

$$BC_{i,j} = W_i \cdot DF_{i,j} \tag{1}$$

$$DF = \frac{5(Var - Var_{\max})}{Var_{\min} - Var_{\max}} \tag{2}$$

$$DF = \frac{5(WIP - WIP_{\max})}{WIP_{\min} - WIP_{\max}} \tag{3}$$

$$DF = -2.5 \cdot TR + 8.75 \tag{4}$$

Table III: Value table for assessing MH flexibility.

Score	System flexibility description
0	System not flexible
1	Changes possible with major amendments of the system, long-term
2	Changes possible with major amendments of the system, rapid
3	Changes possible with minor amendments of the system, long-term
4	Changes possible with minor amendments of the system, rapid
5	Fully flexible

Table III is a general table for assessing MH flexibility. In our case, we decided that the flexibility is our benefit, and the alternative should affect a maximum of 30 % of MH benefit. So, we will transform the benefit scores from the scale 0 to 5 to a scale of 3.5 to 5. In this way, the score changes by a maximum of 30 % and consequently does the impact on benefit. The scores obtained from the original rating scale will be transformed into the adjusted Eq. (5), where $TB_{(0\text{-}5)}$ represents the total benefit or benefit score obtained according to the original scale, and $TB_{(3.5\text{-}5)}$ represents the benefit score according to the new adjusted scale.

$$TB_{(3.5-5)} = 0.3 \cdot TB_{(0-5)} + 3.5 \tag{5}$$

We also limited the number of cost sources in the cost analysis because of the large number of scenarios we analysed. After consulting with the team, we divided the costs into:

- Purchase costs (price of the investment in transport equipment, price of MH installation),
- Operating costs (energy cost, maintenance cost, cost of operator’s salaries).

The price of the investment in equipment was obtained from catalogues, presentations of transport equipment providers and team consultations. Prices vary depending on the specific utilisation of the equipment; however, the rough price serves as a good starting point for comparing individual systems. The prices of MH installations are added in cases, where an additional cost arises due to the introduction of the system. This is mainly in the testing and deployment of AGVs and in the adaptation of rooms where transporters will be used. For ecological reasons, it was assumed that the transport equipment was powered by electricity. The cost of energy was calculated from electricity consumption, electricity price and the share of time the vehicle is operating. Because of the diversity of transport equipment, services and warranty contracts, the maintenance cost was taken into account as a percentage of the investment price in transport equipment per year, namely maintenance for one-shift work 3 % of the system purchase value per year, for two-shift 4 % of the system purchase value per year and for three-shift 5 % of the system purchase value per year. The cost of the operator's salary was set to be € 18,000 per year, which is approximately € 800 monthly net salary of the operator. The sum of all the costs of each alternative j totals in the total costs S_j.

For the value-based CBA, all previously obtained total costs S_j are combined with the total benefit TB_j of the j^{th} alternative. They are compared to the cost-benefit ratio K_j of the j^{th} alternative, see Eq. (6). The alternative with the highest cost-benefit ratio is the most appropriate choice.

$$K_j = \frac{TB_j}{S_j} \tag{6}$$

4. RESULTS AND DISCUSSION

4.1 Influence of parameter selection on MH

Before the final results, an analysis of the influence of parameter selection on the efficiency of individual MHs was performed. The results are shown as the average of all relevant scenarios (Fig. 1). They are shown with average transport times, as these most clearly reflect the improvement and deterioration of the system efficiency. Since the changes in the parameters lift presence and unit load impact the number of required resources, the average number in all relevant scenarios is shown in Fig. 2. Changing the parameters does not affect the system of transporters.

In multi-storey production facilities, the use of a goods lift increases the average transport time by 73 % in the forklift approach, by 119 % in the milk-run system, by 24 % in the AGV systems and by 56 % in the rack system with AGV (a section of the Process Flow model in FlexSim with a section of layout is shown in the Fig. 3). The most extended times are encountered in the milk-run systems due to the operation of a single train, while the number of means of transport increases by an average of 100 % in the forklift approach, due to the presence of a lift, and by 78 % in the AGV systems. The rack system with AGV proves to be the best, with a small change in transport times and an unchanged number of means of transport. Due to the operating mode of this system, the transport times without the use of a lift are already very long and therefore the presence of a lift has less of an effect on the transport times.

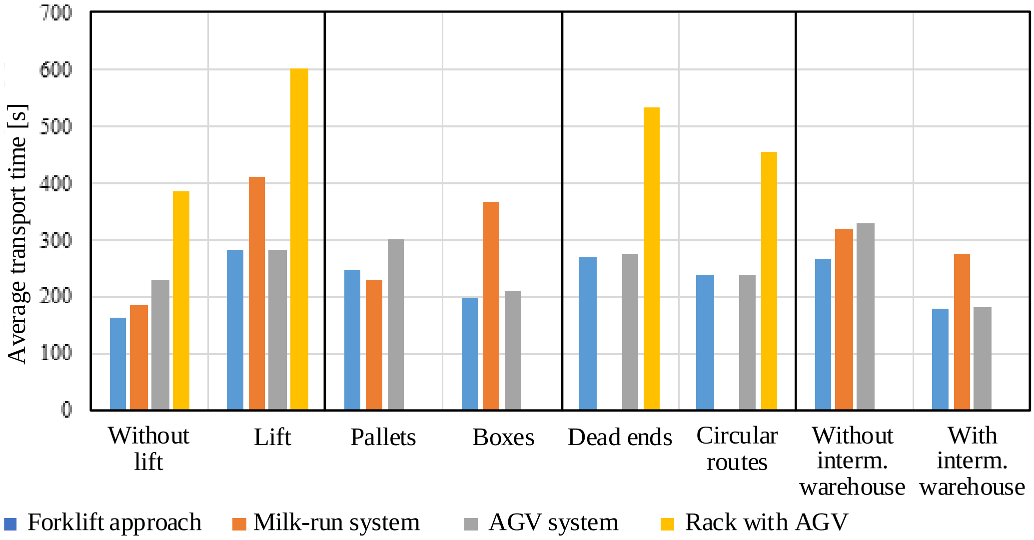


Figure 1: Average transport time according to the selection of parameters.

The intermediate storage warehouse is closely linked to the use of a lift, as the presence of an intermediate storage warehouse in a production facility reduces the occupancy of work equipment due to the lift by 35 % in the forklift approach, and by 50 % in the milk-run and AGV systems.

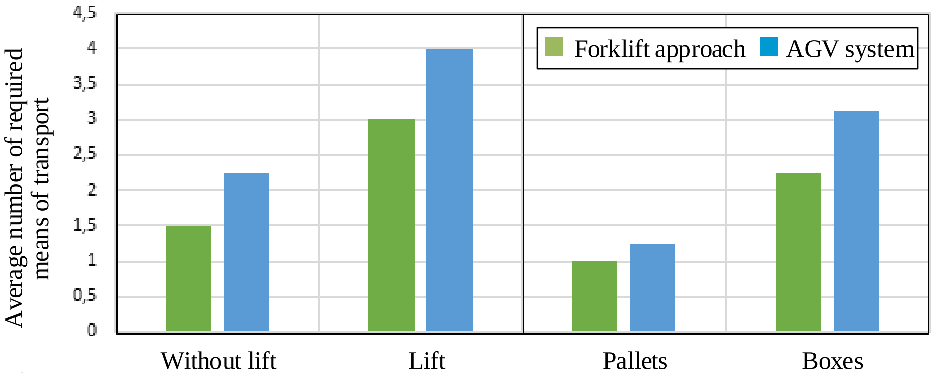


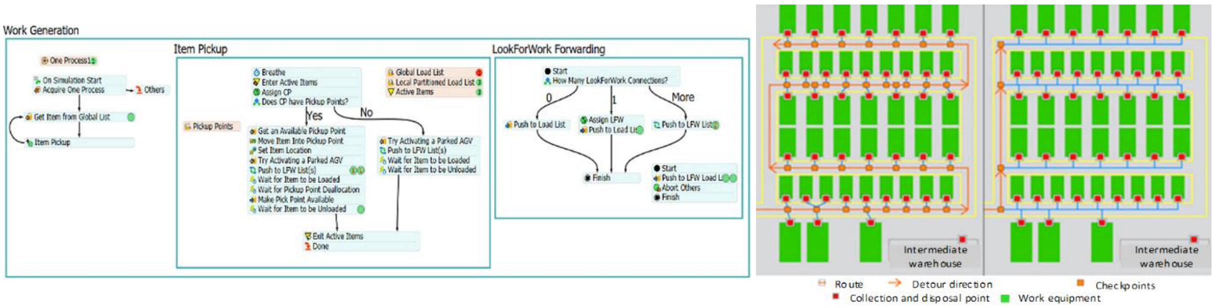
Figure 2: Average number of means of transport according to the selection of parameters.

Lower lift occupancy is also reflected in the average transport times which are reduced by 32 % in the forklift approach, by 14 % in the milk-run systems, and by 45 % in the AGV systems.

An intermediate storage warehouse is the best contribution to the efficiency of AGV systems because it reduces congestions in front of the lifts due to the large number of AGVs.

The rack system with AGV has not been tested with an intermediate storage warehouse because the racks as such serve as an intermediate storage warehouse.

Various layouts of transport routes have been introduced mainly because the layout with dead ends prevents the introduction of a "milk-run" system. However, the average transport times in all MHs were reduced by an average of 13 % due to the shorter required transport distances.



a) b)

Figure 3: A section of the Process Flow model in FlexSim (a) with a section of layout (b).

The difference in the unit load form, in addition to the difference in material flow, also presents technical and logistical challenges. Due to the problems linked to the technical implementation and the associated increased costs of pallets as unit loads, no simulation was done for transporter systems and rack systems with AGV. By switching from a pallet system to a box system, the average transport time is reduced by 21 % in the forklift approach and by as much as 30 % in the AGV systems, which is contrary to expectations as the box system represents a higher material flow. The reason for the deviation from the expected results is to be looked for in the required number of means of transport, which increases by an average of 125 % in the forklift approach and by 150 % in the AGV systems.

On average, the cost of investment in transport equipment more than doubles in these systems, while the efficiency does not improve proportionally. The milk-run system proves best when a box is used as a unit load, as it responds to the increased material flow with an increased capacity of trailers, while the number of means of transport remains unchanged.

4.2 Results of CBA and selection of the most suitable MH

A total of 48 different simulation scenarios were performed depending on the ability to implement MH. 16 scenarios were carried out for the forklift approach, 8 scenarios for the milk-run system, 16 scenarios for the AGV systems, 4 scenarios for the system of transporters and 4 scenarios for the rack system with AGV. The scenarios, in which a change in parameters only affects costs, were not simulated separately. All parameters were divided into two levels (Table IV) and 32 scenarios were defined according to the parameter level (Table V). The average transport time, the required number of means of transport, the total annual costs and the benefit assessment for all feasible MHs in the scenarios are shown in Table VI.

The most suitable MH based on the CBA results were presented in decision trees. An example of a decision tree for three-shift work is shown in Fig. 4. The names of parameter selection in the test nodes are abbreviated for better transparency of the decision trees. A need for a lift is abbreviated to "lift", the presence of an intermediate storage warehouse to "intermediate storage warehouse", the presence of workers at WE to "workers at WE" and the unit load type to "unit load". The parameter transport route layout is abbreviated to "route layout", "dead end" represents a layout with dead ends, "circular" represents a circular route layout.

Table IV: Parameter levels.

Parameter	Parameter level	Value
Lift	Lift present	1
	Lift absent	-1
Intermediate storage warehouse	Intermediate storage warehouse present	1
	Intermediate storage warehouse absent	-1
Route layout	Circular route	1
	Dead ends	-1
Unit load type	Box	1
	Pallet	-1
Workers at WE	Workers available	1
	Workers not available	-1

Table V: Parameter levels in scenarios.

Parameter	Scenarios																															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Lift	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1
Intermediate storage warehouse	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1
Route layout	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1
Unit load type	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1
Assistance of workers	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table VI: Selected results of simulations and cost-benefit analysis for all scenarios.

	Forklift approach				Milk-run				AGV system				Transporter				Rack with AGV			
Scen.	*ATT* [s]	*n* [/]	*TC* [k€/a]	*BS* [/]	*ATT* [s]	*n* [/]	*TC* [k€/a]	*BS* [/]	*ATT* [s]	*n* [/]	*TC* [k€/a]	*BS* [/]	*ATT* [s]	*n* [/]	*TC* [k€/a]	*BS* [/]	*ATT* [s]	*n* [/]	*TC* [k€/a]	*BS* [/]
1	284	1	54.4	4.74					481	1	30.9	3.95								
2	424	1	59.8	4.44					448	2	42.9	4.14								
3	153	1	54.3	4.96					170	1	58.1	4.63								
4	198	1	54.4	4.83					239	1	58.1	4.48								
5	217	1	54.4	4.86	168	1	59.5	4.95	325	1	30.8	4.39								
6	379	1	59.7	4.51	382	1	59.4	4.61	403	2	44.3	4.23								
7	147	1	54.4	4.98	152	1	59.4	4.95	143	1	59.4	4.7								
8	191	1	54.4	4.85	214	1	59.4	4.77	204	1	59.4	4.55								
9	101	2	119.2	4.86					226	2	25.6	4.42	102	1	73.1	4.52				
10	290	3	177.2	4.66					290	4	79.7	4.41	102	1	73.1	4.52				
11	78	2	119.2	4.89					137	3	62.4	4.58	102	1	96.6	4.52				
12	275	3	177.2	4.69					212	4	108.6	4.42	102	1	96.6	4.52				
13	185	1	60.9	4.77	208	1	60.3	4.75	186	2	25.6	4.49	102	1	73.1	4.52				
14	249	3	177.1	4.75	522	1	60.1	4.43	96	4	79.7	4.42	102	1	73.1	4.52				
15	143	1	61	4.83	219	1	60.4	4.72	163	2	54.6	4.48	102	1	96.6	4.52				
16	258	3	180.9	4.7	522	1	30.1	4.42	195	4	108.6	4.46	102	1	96.6	4.52				
17	284	1	54.4	4.74					481	1	24	4.06								
18	424	1	59.8	4.44					448	2	36	4.26								
19	153	1	54.3	4.96					170	1	51.2	4.75								
20	198	1	54.4	4.83					239	1	51.2	4.6								
21	217	1	54.4	4.86	168	1	59.5	4.95	325	1	23.8	4.51								
22	379	1	59.7	4.51	382	1	59.4	4.61	403	2	37.4	4.35								
23	147	1	54.4	4.98	152	1	59.4	4.95	143	1	52.5	4.82								
24	191	1	54.4	4.85	214	1	59.4	4.77	204	1	52.5	4.67								
25	101	2	119.2	4.86					226	2	18.7	4.54					417	1	1.5	4.38
26	290	3	177.2	4.66					290	4	72.8	4.52					652	1	16.3	4.06
27	78	2	119.2	4.89					137	3	55.4	4.7								
28	275	3	177.2	4.69					212	4	101.7	4.53								
29	185	1	60.9	4.77	208	1	60.3	4.75	186	2	18.7	4.61					355	1	16.5	4.45
30	249	3	177.1	4.75	522	1	60.1	4.43	96	4	72.7	4.59					554	1	16.3	4.34
31	143	1	61	4.83	219	1	60.4	4.72	163	2	47.6	4.59								
32	258	3	180.9	4.7	522	1	60.1	4.42	195	4	101.7	4.57								

Legend: *ATT* [s] – Average transport time in seconds; *n* [/] – Number of means of transport; *TC* [k€/a] – Total annual costs in thousands of euros; *BS* [/] – Benefit score.

The more shifts, the more favourable choice is automated systems, i.e. an AGV system, a transporter system and a rack system with AGV. In one-shift work, automated systems are the most appropriate choice in 22 % of scenarios, in two-shift work they are the most appropriate choice in 53 % of scenarios, and in three-shift work they are the most appropriate choice in 75 % of scenarios.

The result obtained was expected, as the highest variability in the cost analysis depending on the number of shifts is due to the salaries of operators.

A unit load form also has a noticeable influence on the selection of MH. This is due to the lower material flow density in case the unit load form is a pallet. If we look at the selection of MHs in all three types of shift work, the investment in automated MHs pays off in 40 % of the scenarios where the unit load is a pallet and in 60 % of the scenarios where the unit load is a box.

In general, in all scenarios for all three types of shift work, the forklift approach is the most appropriate choice in 37 % of scenarios, the milk-run system in 14 % of scenarios, the AGV system in 29 % of scenarios, the system of transporters in 8 % of scenarios and the rack system with AGV in 12 % of scenarios. Interestingly, the forklift approach, which, theoretically, is the system with the lowest efficiency, is selected most often. This is due to scenarios in which the unit load is a pallet.

In these scenarios, the material flow density is low enough for one operator using the forklift approach to pick up and deliver units of loads in the fastest way. This was shown by the benefit analysis. The forklift approach and the milk-run system are very close as far as the cost analysis goes.

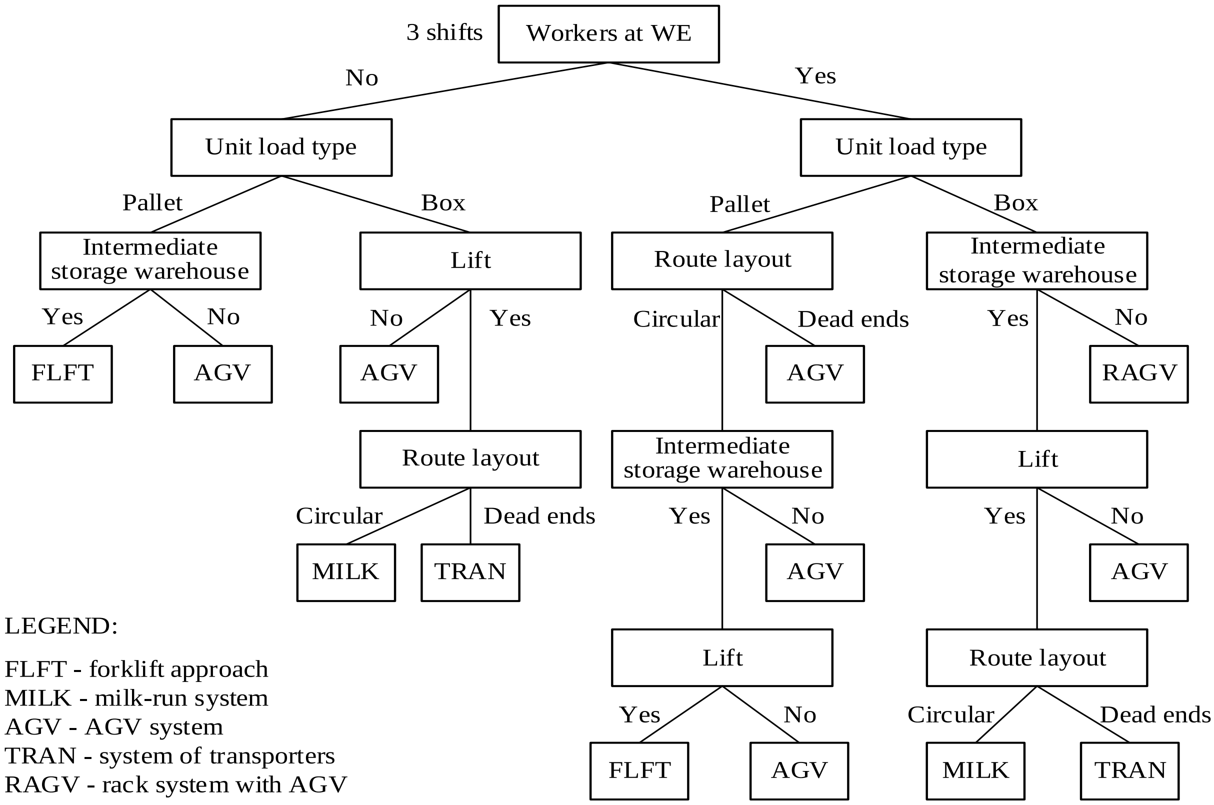


Figure 4: Decision tree for selecting the most suitable MH for three-shift work.

For this reason, the milk-run system is the best choice in a smaller number of scenarios. The second main reason is there are no selection options in a half of the scenarios, as a circular transport route layout is needed for the operation. Yet another reason is that the rack system with AGV is a better choice due to the low initial investment required even in cases when a milk-run system would in fact be the best choice.

The system of transporters is the best choice in the smallest number of scenarios, as it requires an extremely high initial investment. In addition, it is not suitable for the scenarios in which a pallet is the unit load. It is assumed that the investment in the system of transporters would not be justified, even if the system could be established, due to a low material flow density of pallets. However, the rack system with AGV is the best choice in all scenarios where it can be set up.

The studied company has a wish to transition to a system in which boxes are used as unit loads. This would reduce the area next to the WEs now occupied by pallets while being loaded with boxes. As a result, less problems would be encountered during machine repairs, the problems linked to ensuring a sufficient width of transport routes for the means of transport would be reduced. In addition, the company wants the workers at the WEs not to be involved in the transport of unit loads. They want to eliminate the intermediate storage warehouse to gain extra space for WEs in the production, while it is impossible to avoid the need to use a lift. They are in favour of changing the layout of transport routes by switching from a layout with dead ends to a layout with circular routes, if this contributes to a reduced investment in MH. If these parameters are checked in the decision tree for three-shift work, it can be observed that all comes down to the last test node which is the choice of the layout of transport routes. If circular routes are selected, the milk-run system is the most appropriate choice, but if a layout with dead ends is selected, the best choice is the system of transporters. The data from Table VI show that in case of a layout with dead ends the cost of investment in the system of transporters is € 73,127 per year, and the investment cost for a milk-run system in case of a circular route layout is € 60,125 per year. So, if the WEL and the layout of transport routes are changed, € 13,000 can be saved per year if the above identified desired parameters are set up.

5. CONCLUSION

This paper outlined the selection of the most suitable material handling system in a production facility. Our research was based on an actual production of injection moulded components for the automotive industry. The parameters in the production facility were changed in a way that the results are representative of general production plants. Generalized simulation models for 5 different material handling systems were designed and optimized using data obtained from the models. Based on 5 different parameters in production, 32 different scenarios were designed and generalized simulation models of material handling systems were adapted for each scenario provided the parameters allowed it.

Using data from simulations and data on material handling equipment, a cost-benefit analysis was performed for all scenarios. Based on the assessment of the analysis, a 75 % difference between the most and least favourable scenarios was established. A data analysis from simulations was performed to show the influence of parameter selection in production on the efficiency of material handling systems. Based on the cost-benefit analysis, the selection of the most appropriate material handling system depending on the choice of parameters in production was represented in the decision trees.

To select the means of transport in the selected production systems, the proposed simulation model could be upgraded by expert systems. This could reduce the number of scenarios as the scenarios would be evaluated in advance on the basis of expert knowledge. Nevertheless, the use of the proposed system is sufficient for practical use since it can be used as early as the phase of optimal layout of machines in a production plant, so that companies can decide for the most suitable MH system in the planning phase and avoid subsequent costly changes and corrections.

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