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Optimization opportunities in matrix production

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Abstract: Nowadays, due to rapidly changing customer needs, product life cycles are getting shorter, while the number of product variants is increasing, so continuous innovation of the product and the technology related to its production is an important task. Not only the product itself needs to be renewed, but also flexible production technology needs to be developed in accordance with changing customer needs, as a large number of product variants are being produced, which require individual settings, different production operations and real-time tracking. In the case of diversified manufacturing requirements, the application of Industry 4.0 technologies can increase efficiency. The aim is to maintain the smoothness of the manufacturing process, for which matrix production offers a suitably flexible solution. The main tasks of production logistics are the in-plant movement of workpieces between workstations and the supply of workstations with the raw materials, parts, etc. required for the actual production step. The larger workpieces are transported by dedicated AGVs. In the production area, several AGVs can perform their tasks simultaneously, so several material handling tasks occur at the same time. This paper deals with the route planning issues emerging during the movement of AGVs between the workstations in a multi AGV environment. We are following a holistic approach during design, aiming to simultaneously optimize layout, production sequence, and AGV routing.

1 Introduction

Due to the rapidly changing customer demands, the life cycle of the products is shortened, diversity is increased while the number of products per model is reduced [1], so there is a need to constantly work on the product's innovation and the production-related technologies. Due to the diversification mentioned above, there is a need for an innovative and scalable production system that can handle the rapidly changing needs and uncertainties. A high degree of flexibility associated with high output performance and scalability is also essential [2]. All of this can be accomplished through digitization and networking for an Industry 4.0 company.

The introduction of Industry 4.0 and the rapid development of cyber-physical systems, as well as the increasing demand for small batches and customized products, present a significant challenge for traditional manufacturing systems [3]. Improvements need to focus on solutions that help reduce the relative cost of labour, energy and machinery. This requires end-to-end data integration in the supply chain [4], automated material flow, and real-time communication. All of this requires the development and implementation of new manufacturing structures and solutions. One such new solution is matrix production.

2 Literature review

The smart factory is based on the concept of Industry 4.0, denoting technologies and concepts related to cyber-physical systems and the Internet of Things. In smart factories, computer physical systems monitor physical processes, create a virtual instance of the physical world, and make decentralized decisions. CPSs communicate and collaborate with each other in real time [5].

The manufacturing industry needs the highest quality products and services to maintain its competitiveness in the consumer market [6]. Virtual commissioning (VC) could be one of the main applications of future simulation solutions in the automotive industry. In case of a new component integration, before any physical changes are made in the factory, a simulation can be run and, if successful, the device can send feedback to perform the reconfiguration process in a real factory environment [7].

The matrix production concept allows the free interconnection of production cells and thus removes the limitations of line-based production. Many product variants can be produced within a single production structure.

The duration of a single process step no longer determines the entire production cycle. Rather, the process steps are executed independently to create an infrastructure focused on processes and capacity requirements. However, the implementation of manufacturing cells requires control methods that allow capability-based descriptions of machining processes. This forms the basis for the rapid reconfiguration of cells and efficient adaptation to new manufacturing tasks [8].

Matrix production has a higher degree of freedom due to its flexibility, but also requires more reliable manufacturing control systems than, for example conventional line-based production systems. Matrix production separates automated goods production from the steps necessary for their creation. These steps are assigned to production cells (PCs). Numerous workpieces enter the production cell, where a specific workflow is applied to the workpiece, and the modified workpiece leaves the production cell. By changing the path of the workpieces passing through the cells during production, entirely different products can be created. This highly flexible idea demands precise control of all processes. An intelligent logistics solution transports the goods between the production cells. Information exchange in this complex system requires appropriate communication technology [9]. The data infrastructure required for matrix production needs to be broken down into manufacturing data, including timestamps, process parameters, and assembly locations, testing information, variable threshold values, and information regarding inspection depth and material infrastructure. To facilitate the desired improvement in productivity and particularly the reduction of bottlenecks, it is essential to ensure the accurate correlation of manufacturing and testing data in real time for each production and testing step. Machines requiring complex installations should be considered part of a more complex system rather than standalone machines [10].

Generating the right manufacturing sequences increases machine utilization without hindering the original multidimensional production goals. Thus, new production strategies can be implemented, which involve value creation through the efficient manipulation of smaller products and by-products [11].

During operation, computerised physical work cells generate data specific to individual processes and interaction data. The use of employee, processing, and interaction data enables the support and training of employees according to their individual capabilities. Matching machine requirements and worker skills serves to optimize the assignment of workers to workstations in terms of ergonomic workplace settings and machine efficiency [12]. The digital twin can be considered as a new concept that includes foresight, assesses the impact of different production control policies on system performance and behaviour in near real-time, thus allowing the selection of the most appropriate strategy for the given situation.

Numerous examples of ideal systems projected for the next decade can be found, such as the PSA (Groupe PSA-The Multi-Silhouette Production Line) multi-silhouette production line and experimental plants based on matrix production, like the paradigm proposed by KUKA, which represents a recent effort to break down the traditional linked production line into standardized and categorized production cells along a grid layout [13].

The introduction of AGVs significantly improves the efficiency of internal logistics, reduces the risk of accidents, and increases the organization of processes [14]. These results confirm the growing interest in automation, which contributes to reducing costs, increasing revenues, and meeting environmental regulations.

The route planning and scheduling strategy of material handling vehicles is a central element of the production logistics system, and the quality of the scheduling algorithm is key to the balance and stability of the system. For systems with multiple AGVs, route planning is even more complex. The use of multi-function automated guided vehicle (AGV) transport systems improves the flexibility of the FMS, which places higher demands on AGV scheduling algorithms [15].

Hu et al. combined the Improved Iterative Local Search (IILS) algorithm with greedy heuristic rules, considering the constraints of transportation time and transportation resources [16]. In planning collision-free routes, the combination of the improved Q-Learning (IQ) and democratic robotics particle swarm optimization (DRPSO) algorithm proved to be advantageous [17].

Finding the shortest collision-free path between given sets of targets in a robot's working environment poses a multiobjective path planning problem. On the one hand, the order of the targets has to be optimized and then the shortest path has to be determined. A genetic algorithm can be used to optimize the order of the destinations to be visited [18].

A mixed integer programming model created for minimizing the delay time of AGVs is based on path optimization and integrated scheduling. The combination of genetic algorithm and particle swarm optimization (HGA-PSO) can be used to solve the AGV path conflict or deadlock problem [19]. A solution to the same problem can be developed by implementing the Dijkstra method in the case of hierarchically handling conflicts between nodes [20].

When examining the AGVEESR (automatic guided vehicle energy-efficient scheduling problem with release time) in matrix production – with the help of a multi-objective greedy algorithm (MOGA) – energy consumption, the number of AGVs used and customer satisfaction can be simultaneously optimized [21].

A dynamic AGV scheduling model, unlike a static one, is capable of reassigning AGVs to new tasks. Li et al. used a discrete invasive weed optimization (DIWO) algorithm to prove the efficiency of the new model in matrix production [22].

In the literature, there are many articles dealing with matrix production and the scheduling of material handling tasks in systems using multiple AGVs, but only a few are integrated with the two topics (the Scopus search engine returns four hits for the words "matrix production" AND "automated guided vehicle"). Taking these into account, we defined the research task, in which we deal with the examination and design issues of matrix production using multiple AGVs.

3 Examined system: a factory sample

The factory of the future requires a reliable, easy-to-change, flexible production system. Modular manufacturing involves several changes in design, system, and processes [23], but it usually means that manufacturing must be divided into separate cells instead of a continuous line. Manufacturing and assembling the modules at separate stations allows for greater flexibility in the overall output, including changing product options or changing demand. The intelligent matrix production provides a solution to these.

Some of the most significant advantages of matrix production are the high availability for modularity through standardized equipment; scalability of the total capacity; the possibility for the system's size to be expanded modularly; the scalability being implemented according to different variants; the flexibility related to the types, which is part of the base concept; the scalability of the product mix, which allows to compensate for fluctuations in demand, making the integration of new products simple and low-risk [24].

When the products to be manufactured are changed, the production cells automatically switch to the new tasks. The transformation of the cell takes place in parallel with the production in the other cells. After the transformation, the new unit will be manufactured. During testing and maintenance, cell production tasks can be transferred to other cells.

Through the example of a model factory, we show how to ensure flexibility and a high degree of efficiency with the help of modern, automated machine tools, flexible assembly stations, and autonomous material handling equipment and as well as how to determine the optimal design of the logistics system by exploiting the possibilities provided by simulation.

The factory has one entrance where the workpieces arrive and one exit leading to the finished goods warehouse. Additionally, there are predefined locations for an AGV pool (AGV-POOL), a parts warehouse (WAREHOUSE), and a tool store (TOOLSTORE) (Figure 1).

A dedicated AGV transports a given workpiece through the entire production process from the entrance to the exit. Up to six vehicles can be present at the ENTRANCE and EXIT locations simultaneously for loading and unloading, representing the limited space available.

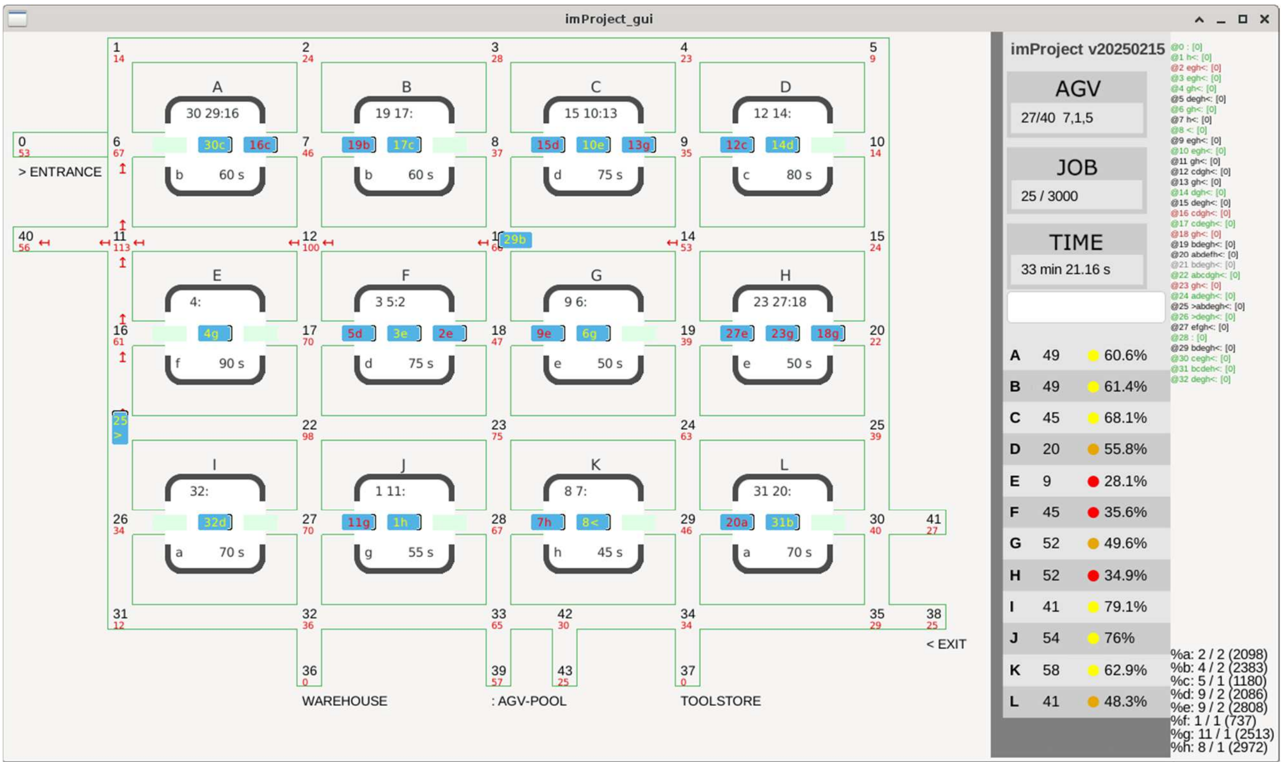

Figure 1 Visualization of the sample factory

3.1 The manufacturing cells, the layout

In the manufacturing area, cells are installed in a matrix layout, bordered by transportation routes. Cells are deployed in several rows and columns. The number of manufacturing cells that can be placed is limited by the available area only. A manufacturing cell is a designated area for carrying out specific tasks that arise during a technological process.

Machines may have different installation characteristics and specific requirements, so not every layout unit may be suitable for placing any equipment. In the model we examined, to increase flexibility, we applied the following conditions:

- cells of identical size were created,
- the cells are equipped with basic robots so any technological operation for any product to be manufactured can be performed in any cell after the necessary retooling,
- the cells are standardized with product-neutral equipment and product-specific basic functions,
- the same type of operations can be performed in each cell a the same time for all products,
- if multiple operations, tasks, or technological steps are carried out in one cell, they are considered a single unit (one operation, etc.) from the model's perspective.

The cells and transportation routes are set up throughout at all available areas at the base configuration level (Figure 1). Depending on the specific manufacturing task and any expected (e.g., planned maintenance) or unexpected events (e.g., malfunction) that arise, the economical operation is maintained by dynamically determining which cells participate in which operations during production. Since the number of technological processes may be less than the number of available production cells, it is possible for multiple cells to perform the same operation in parallel. In the event of an unexpected failure or planned shutdown, another cell can take over the tasks of the failed cell, ensuring uninterrupted production.

In the cells, an input and an output waiting area can also be provided, which does not block the ingress and egress paths. The workspace itself is located between these two areas. The examined model may have input and output buffer areas. The impact of these on the total manufacturing time will be examined later.

The cells can be directional, meaning that, for the given production program, the entrance and exit of the cell are precisely designated. Alternatively, they can be designed to allow any side to be the entrance, making them direction independent. In the examined model, the cells are directional.

The example factory has 3x4 cells, identified by capital letters (A, B, ..., L), while the production includes 8 technological processes, marked by lowercase letters (a, b, ..., h).

When choosing the size of our example factory, we made sure that it was large enough to demonstrate and validate the methods and their applications, while still being manageable in terms of hardware and time, so that the solution to the problem could be achieved within a reasonable time frame.

It is also worth monitoring the utilization of the cells, as this information helps in intervening, deciding on changing, reorganizing, or stopping the processes within the cells.

Any technological operation can be performed in any of the manufacturing cells; thus, a very large number of tasks can be assigned. If a different task is assigned to a cell, we consider those cells different and classify them as different from the perspective of possible layouts. Although the cells are in a fixed location, they can be equated with various machines based on the manufacturing processes carried out within them. The optimal layout can be determined by examining all combination of cell sequence and orientation and then comparing the results for each production sequence, considering the routing rules detailed later.

During the optimization, various objective functions can be specified, such as: minimizing the distance travelled, minimizing the time required for production, maximizing capacity utilization, reduction of downtime, minimizing the energy consumption, and minimizing the costs.

In our sample factory, we minimize the time required for manufacturing. For production with similar time requirements, solutions that keep downtime to a minimum are preferred. Energy consumption is proportional to the distance travelled, which can be calculated from the material handling distance (knowing the speed). An important element of layout planning is the proper utilization of capacities.

3.2 Software

The digital twin of the production process is a software created by us, suitable for scheduling production tasks and assigning material handling tasks. The software consists of three main components, these are:

- the simulator - which visually shows the operation of the plant in real-time for a given layout,
- the scheduler – which performs the production in the given order for the given layout,
- the layout variator (LV) - which sends the scheduler through all possible layouts.

Input parameters:

- list to be manufactured denoted with letters (abefgh), one product per line,
- location of ENTRANCE, EXIT, AGV, WAREHOUSE, TOOLS points, cells, nodes on the map,
- working time in each cell, according to the manufacturing process there,

- AGV speed on straight sections, and in bends.

Using simulation of the manufacturing process in any moment of time or duration can be viewed, in fact, the scheduler's output is visualized. The simulation shows the elapsed time since the start of the production, the number of workpieces completed, the number of tasks performed in each cell and the utilization of the cell.

The scheduler's output is the registration of the run information generated during the production in the given order on the time axis t, a detailed decision & action & AGV operation log file is created, later the simulator will use this file. AGVs can have the following statuses: not working, loading, unloading, waiting for production, waiting to proceed, waiting for route. The cell production log (production start, end of production, parts warehouse filling, idle) can be used to check the utilization.

The variator records the following aggregate data for the production with the best N time results: total time (ENTRANCE (0) .. EXIT (n)), average EXIT time, variance, maximum AGV requirement, AGV utilization for each status, utilization data of cells, average preparation time of one product, variance.

If the worst of the top N time is known, then if a production reaches this time before it is completed, the scheduler will stop and give a "not worth counting" status in response.

3.3 *Defining routes for saving computing time and limiting the required memory space*

In the following, we will focus on material handling between workstations during matrix production and the related route planning problems. We searched for an algorithm for route determination that allows efficient movement of workpieces. Additionally, we determined the quantity of AGVs required for these material handling tasks.

Each AGV involved in the production process receives a unique serial number, starting from 1, and going upwards. An AGV must request a route permission if it wants to change its position (e.g., go from cell A to cell C). This prevents vehicles traveling opposite direction between two adjacent junctions, resulting in unexpected congestion. When requesting a route, the AGV can only get route allocation if the destination can receive it (e.g., the production cell is empty, or the input buffer is unoccupied). We are using greedy algorithm to select the route. From the possible routes between the current position and the destination, the shortest one is chosen, on the route of which no other AGV has yet been authorized to travel in the opposite direction. We examine the shortest 32 routes between the two points for saving computing time and limiting the required memory space. If multiple paths of equal length are available, we select them using the modulo residual classes method (the time elapsed since the start of production is divided by the number of good paths and then the sequence number corresponding to the remainder is selected), thus, it can be solved that the algorithm does not always choose the first good solution and load the nodes unevenly. However, since we do not use a random number generator, we always get exactly the same result, log files, for any number of runs (in the case of a production task with the same parameters). The selected route is then reserved (red arrows in the figure), and we will not allow oncoming traffic in any part of the route until this AGV is passed. Each AGV has a safety distance to avoid collisions.

If two AGVs are crossing each other's paths at a junction, the one that arrives first gets priority. If they arrive at the same time, the AGV with the lower serial number can proceed first.

With all these restrictions, it is possible to avoid unnecessary waiting, and to avoid congestion in front of the input buffer of a cell, which would obstruct the traffic, and to keep the material handling path as short as possible.

The flowchart in Figure 2 on the next page illustrates the request for a route from point P to point Q. The algorithm is executed every single time the AGV get a material handling task. The routes from P to Q are stored in the rows of the cache matrix. The rows of the matrix lists the individual points on each route that the AGV must visit in the given order.

The notations used in the figure:

- i: index variable for route cache entries,
- j: index variable for allocation of path segments,
- k: index variable for deallocation of path segments,
- $u_{i(max-1)}$ penultimate element of the i-th row,
- u_{ij}: j-th element of the i-th row of the cache matrix,
- u_{ik}: k-th element of the i-th row of the cache matrix,
- U_{max}: number of rows of the cache matrix.

Stochastic effects related to AGVs (e.g. blocking, failure, handling delay, communication failure) have been built into the simulation software. A file containing the time and duration of unexpected errors and delays can be generated before the run. The resulting file is generated randomly taking into account the predefined parameters. Since the measurement results must be reproducible and comparable, the file must be available before the run. Of course, any number of files can be generated, which is of great importance if we want to examine the impact of unexpected problems more comprehensively.

When determining the route, the following constraints and neglects are applied:

- The number of AGVs has an adjustable upper limit.
- AGVs are unified, they cannot reverse, they have two constant speeds (on a straight road, in a bend).
- Routes between and around cells are single-lane, rounds are not curved.
- Movements within WAREHOUSE, AGV-POOL, TOOL STORE are not examined, only an average time spent there is considered.
- Each AGV is responsible for the transportation of one workpiece from entrance to exit through the required cells.
- One AGV transports up to one workpiece at a time.

- If an AGV wants to change its position, it asks for route allocation, which determines the exact trajectory of the relocation. Multiple AGVs moving in one direction may be present on one section (branch to branch), keeping the appropriate distance.
- We do not allow two-way traffic on the reserved route.

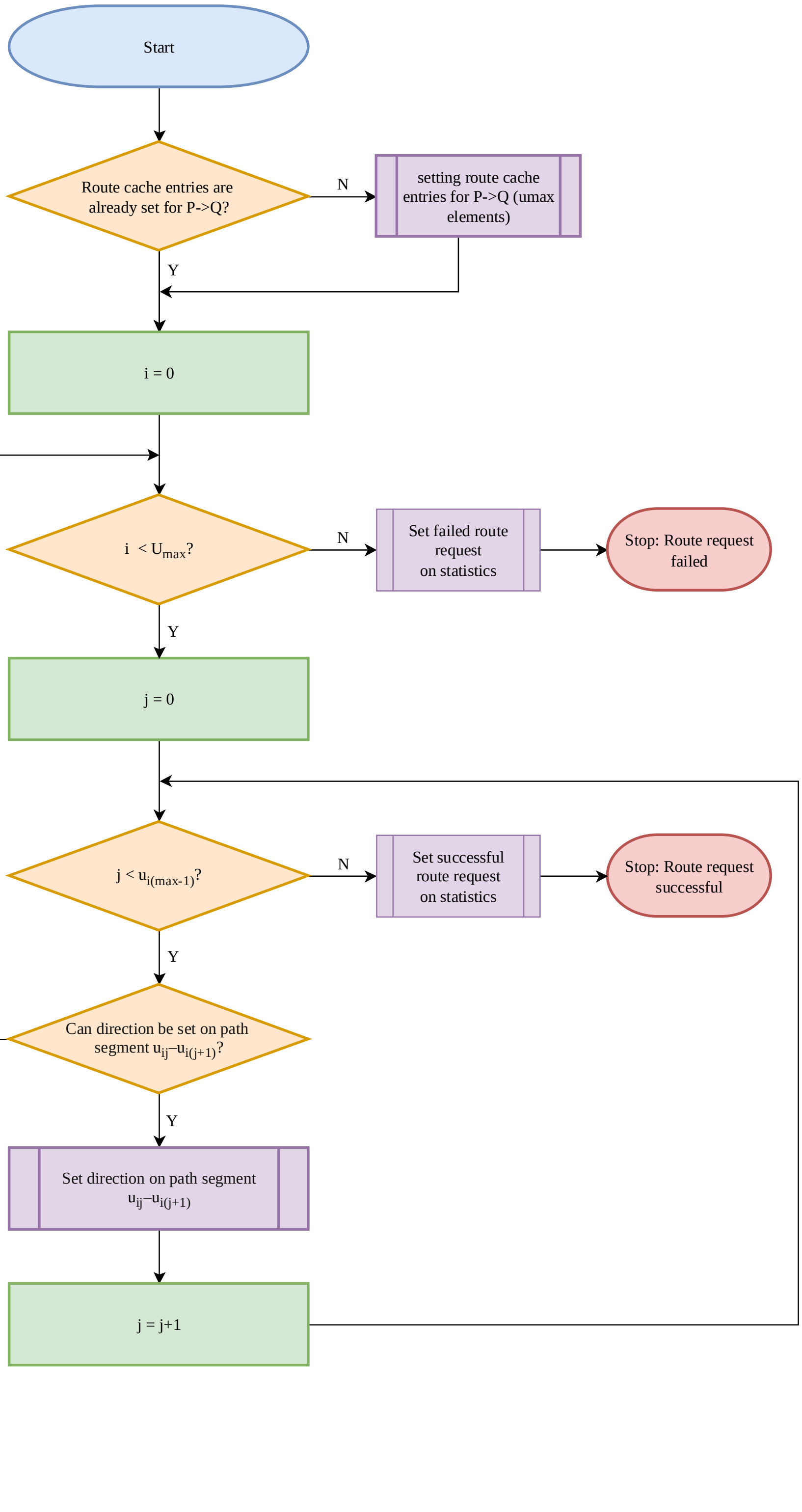

Figure 2 Flowchart of requesting a route allocation from point P to point Q

3.4 *Determining the products to be manufactured*

The sequence of products to be manufactured was randomly generated in the following way. For each operation, we used a probabilistic variable to determine whether the task is part of the product's manufacturing process. Each manufacturing process consists of up to 8 operations, any of which can be omitted – simulating product diversity – but the sequence always follows alphabetical order (e.g., cfgh). Thus, 2^8-1 different products can occur. The quantity of products to be manufactured was fixed at 3000.

Each manufacturing process (a to h) has the following probabilities for each product: a: 71.17%, b: 80.83%, c: 39.80%, d: 70.50%, e: 94.73%, f: 24.80%, g: 84.70%, h: 100.00%. Using all this, we generated and organized a production process list for 3000 products. The rows of the production list represent the products to be manufactured with the necessary technological operations. For example, for the row cfgh, tasks c, f, g, h needs to be performed.

Such a solution may involve visiting cells D, E, J, K (Figure 1). From now on, we will consider the products listed in this 3000-item list as required by the production program.

3.5 *Determining the number of AGVs*

We examined a randomly selected layout in terms of how the waiting, movement and production times change as a function of the number of AGVs. Choosing the number of AGVs has a positive impact on the total manufacturing time and cost levels. Production slows down if there are too few AGVs to serve, but it also slows down if there are too many, as they obstruct each other's movements, significantly increasing waiting times and generating unnecessary costs. To determine the optimal number of AGVs, the scheduler must be run with various quantities of AGVs, and the results should be compared (a specific example will be presented later).

We examined the placement of each layout in terms of how the waiting, movement and production times change as a function of the number of AGVs. Later in the article, we will present in detail the variation of the times described above as a function of the number of AGVs in a given layout.

4 Optimization possibilities and results

The optimization process was divided into three main segments (Figure 3), these are the determination of the optimal production sequence, the optimal layout, and the optimal route. The bottleneck is the runtime environment (hardware) and the processing time [16].

Calculation of processing time falls between 1s and 2s on server grade CPU (any high-end Intel Xeon/AMD Epyc) and between 10s and 12s on Raspberry Pi M3 (ARMv8). Each CPU thread can process one layout calculation at a time, meaning a CPU with 128 threads require only 1-2s to process 128 different layouts. Vector processor could offer one or two orders of magnitude increase in layout number calculated in a given time.

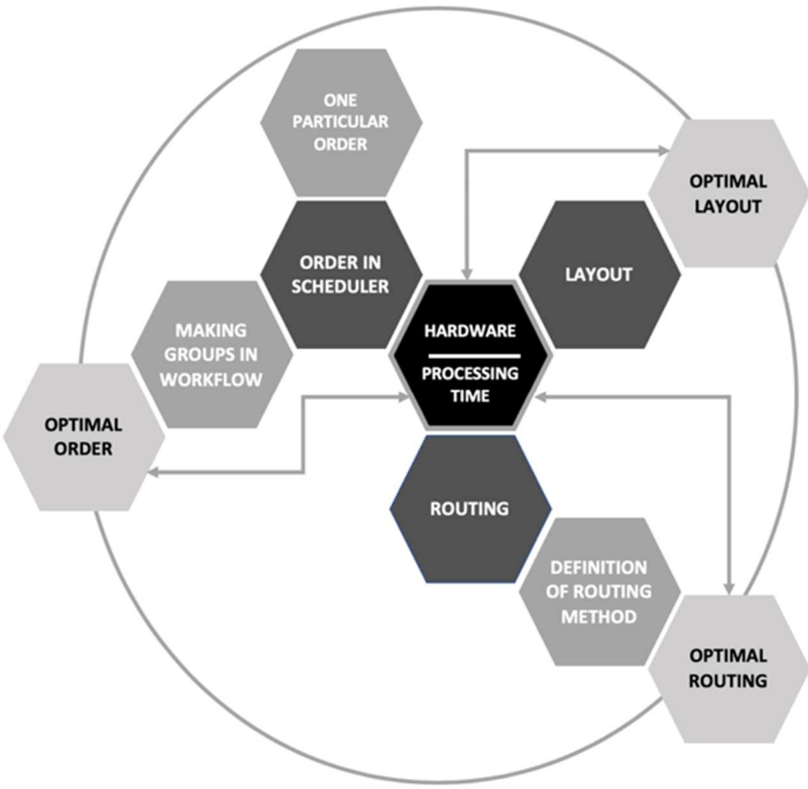

Figure 3 Parts of the optimization task

4.1 Optimization opportunities of cell layout

Manufacturing process consists of up to 8 operations, requiring 8 cells each. It leaves 4 positions to define without further restriction.

4 unrestricted cells can be populated by:

a) all the same (x, x, x, x),
b) three of a kind, and one differs (x, x, x, y),
c) two distinct set of two of a kind (x, x, y, y),
d) two of a kind and two differ mutually (x, x, y, z),
e) diverse (x, y, w, z).

These sets give us the following layout numbers:

a) $\frac{12!}{5!} \cdot 8 = 31933440,$

b) $\frac{12!}{4! \cdot 2!} \cdot 8 \cdot 7 = 558835200,$

c) $\frac{12!}{3! \cdot 3!} \cdot \binom{8}{2} = 372556800,$

d) $\frac{12!}{3! \cdot 2! \cdot 2!} \cdot 8 \cdot \binom{7}{2} = 3353011200,$

e) $\frac{12!}{2! \cdot 2! \cdot 2! \cdot 2!} \cdot \binom{8}{4} = 2095632000,$

A total of 6 411 968 640.

We calculated the gross time for each operation on the whole 3000-item list using processing time and probability values.

Table 1 Total manufacturing time for each operation

a		b		c		d		e		f		g		h	
probability values	man. time (s)	probability values	man. time (s)	probability values	man. time (s)	probability values	man. time (s)	probability values	man. time (s)	probability values	man. time (s)	probability values	man. time (s)	probability values	man. time (s)
2135	70	2425	60	1194	80	2115	75	2842	50	744	90	2541	55	3000	45
149450 s		145500 s		95520 s		158625 a		142100 s		66960 s		139755 s		135000 s	

The summary gives the four highest gross time on operation types "a", "b", "d" and "e".

With an assumption, the optimal layout would be one permutation of {a, a, b, b, c, d, d, e, e, f, g, h}. To prove this theory, we instructed the LV software to run on all the variations (total of 29 937 600) to get the highest time required for the 3000-item list (with AGVs number up to 36, without AGV prioritization, with ingress and egress buffer space on each cell). The best layout seemed "bbdcfdeeagha" with production time of 2424.65 minutes (Table 1).

The best 1000 results with the lowest manufacturing time all suited our prior expectation and contained double 'a', 'b', 'd' and 'e' cells. Layouts with the lowest and highest manufacturing times can be seen on the Table 2.

Table 2 The layouts with the shortest and longest manufacturing times

layout	manufacturing time (min)
bbdcfdeeagha	2424.65
aabdefebdghc	2425.09
abbcefaeddgh	2425.32
cebedaghadfb	2425.42
bdbeaedfacgh	2425.56
aaecefghddbb	2425.87
bgabaeehdfcd	2425.89
eghbeaacbfdd	2425.92
afghbebedcda	2425.97
cbeaefghadbd	2425.98
cfbdeeghdaab	2426.09
dbahfcegdaeb	2426.09
bbafeghaeddc	2426.20
baahefdedcgb	2426.24
efghdebbcaad	2426.26
bdcebfgheaad	2426.34
daadbefcbegh	2426.39
dadbafghebce	2426.45
efedbaghdabc	2426.46
abebdeghafcd	2426.54

layout	manufacturing time (min)
bgchhffaechd	3002.39
afedhffbfhgc	3002.49
eghfffbhfdac	3002.99
hhdcgefhfhba	3003.33
behfgfhcdhfa	3003.44
hffbdcfheagf	3003.72
dcgbffheccca	3003.79
ffchhhdaebhg	3003.87
aghhdgfbeggc	3003.87
eghbgfhfchda	3004.10
bfgcfefhhafd	3004.42
fhfdebfcfafg	3005.08
bhhgffhadecf	3005.12
edgffahfbhfc	3005.63
dhebahfhgchh	3006.21
aefdhhhcbffg	3006.34
hchahefffdbg	3006.45
ahfdhgfbcgef	3007.04
bfgchhehafdf	3007.10
afcgghfhedbh	3011.69

Description for layout 'abcdefghxyzw': $\begin{matrix} a & b & b & d \\ e & f & g & h \\ x & y & z & w \end{matrix}$.

As the computing resources are limited, especially on larger layouts, there is no way to check all the layouts. It is very important to improve our algorithm to avoid unnecessary computation and skip as many variations as possible. This method may not find the best layout but an acceptable, good one.

To achieve our goal, we choose a higher P_H and a lower prime P_L number and shrink our whole variation list to a manageable one.

By using P_H we skip all lines with the exception where row number divided by P_H gives zero remainder. This method reduces the whole variation list from 6 411 968 640 to 2 138 036 elements providing using P_H = 2999. To make the computation even shorter we use the same algorithm to make a second list by using P_L = 13. The double-reduced list has 164 465 elements to probe, lowering the required time of their $\frac{1}{40000}$ value. Since the whole list was ordered and the first and second prime reducer process are both systematic on row numbers, the result expected to contain 'good enough' layout.

Table 3 The layouts with the shortest manufacturing times from the reduced list

layout	manufacturing time
acebdaghfdeb	2432.74
ddebbaghecfa	2433.28
cbghfebaddea	2433.46
eeghcbbddafa	2433.90
aecbdghadbef	2433.96
ecabbahddgef	2434.11
efbbdgcadeah	2434.17
baedafcedbgh	2434.23
dabecbfdeagh	2434.44

The best layouts (Table 3) with the shortest manufacturing time from the reduced list differs only 8.09 minutes (0.33%) to the best time from the whole variation list. At the same time the required run time is only 0.0025% of the initial without any reduction. By choosing the prime numbers wisely it is easy to adjust the required total running time to meet computation potential.

4.2 *Optimization opportunities of the product list*

The product list is a FIFO buffer specifying the sequence of products and also the required production steps for each one. Our sample factory uses a 3000-piece product list to make time measurements and do simulation. We created the first (initial) process list (L_R) by using method on chapter 3.4 and make a second list (L_A) by sorting L_R in alphabetical order. Using the two lists we took a measurement for the layout 'bbdcfdeeagha' (AVGs up to 36, with ingress and egress buffers). The processing time for each list is:

- for random L_R list: 2436.74 minutes,
- for ordered L_A list: 3399.07 minutes.

First reordering attempt

We checked the required gross time for each production step on chapter 4.1. The lowest value is for process 'f'. There is an opportunity to shuffle all 'f' containing processes to the first section of the list L_R, repopulate 'f' cell to another process afterwards, provided there is no 'f' needed there anymore. The two lists need more processing time in total than the initial product time before splitting, even with zero transition time to repopulate 'f' cell to another.

Analysis of the product list

We analyzed the composition of the product list because of the failure of first reordering attempt. The data content of L_R list consists of order and composition sequences.

We needed some way to express the real data content of any product list. A solution arised by Huffman-coding the list and use the file size as quantity of data. (David A. Huffman, 1954, "A Method for the Construction of Minimum-Redundancy Codes"). Moving from theory to practice we chose DEFLATE algorithm, using GNU Project's 'gzip' software to create a LZ77 compressed, Huffman coded lists from their original uncompressed instances. The size of compressed file serves as quantity of data, denoted by M_L. Higher M_L means lower compression ratio (Table 4).

Table 4 The size of compressed and uncompressed files

	size of compressed alphabetical ordered	size of product list after first reordering (byte)	size of initial product list byte)
without compression	19996	19996	19996
compressed	314	2743	3197

Using GNU Project's 'shuf' software we generated another 100 random ordered from L_R. Measuring these modified L_R* lists we got the following results:

- lowest processing time: 2423.99 minutes,
- highest processing time: 2446.69 minutes.

The difference is 22.7 minutes, meaning 0.93% based on the lowest time which is significant. M_L sizes varied between 3165 and 3259 bytes.

Given the fact that randomizing the product lists and measuring its processing time is not a computing power consuming task, it is advisable to try hundreds, thousands, or even more lists to find the best process order.

4.3 Path optimization opportunities

Directional path allocation

According to the directional path allocation, all AGVs request their paths beforehand any transportation to their destination taking in action. This is an analogous operation to bus arbitration mechanism of computer systems. Path allocation eliminated the traffic jams which could be resolved only by very complex reversing, temporary AGV moving and other detour definitions.

The allocation itself makes a direction flag on the affected path segments and alters their neutral direction state. The direction setting remains set on all path segments until the transportation is completed.

For direction settings "left/right" or "up/down" can be set on path segments according to their situation on the factory map. Entrance and exit of the cell stay directional by definition, AGV never does reverse movement or enter the cell via exit gate or leaving from entrance. AGV arriving to the cell indulge its path allocation to be freed. Two path allocations can cross their way on the same junction providing that they are skew lines out of the junction. Any collision is prevented by AGV's auto-driving, auto-braking, and safety distance system.

Multiple path allocation

We have an opportunity to further optimize the path allocation by enabling multiple requests on the same-way policy. All paths consisting of partly or completely identical directional vectors can be grouped and enabled.

The path allocator controller records distinct counters for all path segments:

- zero if unallocated (free to any direction),
- positive integer if rightward or downward allocated,
- negative integer if leftward or upward allocated.

The value of integers counts the actual allocation number. One AGV reached its destination deallocate the complete path on segment-by-segment basis.

Path deallocation on junction crossing

By increasing the maximal AGV number the simulation shows significant elevation in waiting time on path allocation. To decrease unnecessary waiting, it is suggested to deallocate the elapsed path segment on crossing a junction. During the deallocation process, path segments reaching zero promotes another pending AGV to have its way. AGVs have their safety distance which can be used as pre-deallocation the path segment before the junction reached. For most layouts this optimization gives up to 0.4% reduction on total manufacturing time.

Extending cells with ingress and egress buffers

The state of cell can be categorized on the following statuses:

- s(p): process on workpiece,
- s(io): moving workpiece in or out of the cell,
- s(w): wating for the next cell or path allocation,
- s(o): cell is idle.

Making detailed statistics on each status helps reveal workload deficiency and solve AGV congestions.

Analysis of the logs showed significant congestions on status s(w). This observation leads to optionally add an ingress buffer to each cell to provide earlier AGV feed before cell process completed on the previous workpiece. There is a second option to add an egress buffer to free the working area of the cell as soon as possible.

We run a detailed test with the following options regarding ingress/egress buffer options:

- without ingress/egress (00),
- ingress only (10),
- egress only (01),
- ingress and egress (11).

The Table 5 showed the results for the layout 'bbdcfdeeagha' with 10 randomized product lists, AGV number between 18 and 28. The time values are all relative to the buffer option (11).

The results show significant decrease in total manufacturing time if ingress buffer is activated. The egress buffer adds additional minor boost to productivity.

The further run time test is with activated ingress and egress buffers from now on.

Table 5 The impact of the lack of buffer areas on manufacturing time [additional minutes]

Number of AGVs	puffer(s)	list 1	list 2	list 3	list 4	list 5	list 6	list 7	list 8	list 9	list 10
18	00	930.47	925.44	927.17	907.06	921.71	915.84	921.04	925.18	922.15	938.27
18	10	31.41	21.84	31.59	28.01	24.85	33.47	21.02	30.12	29.48	20.10
18	01	529.73	535.59	530.54	518.70	522.34	531.71	526.99	534.67	533.55	536.20
18	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	00	976.25	944.77	968.83	977.41	969.06	985.02	958.09	980.26	987.54	981.43
19	10	43.87	34.00	38.44	44.00	44.37	45.47	31.91	34.46	47.16	43.40
19	01	573.97	583.54	589.78	576.16	597.34	580.97	569.82	582.30	584.48	588.66
19	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	00	1014.72	1000.37	1015.23	1003.46	1010.43	1009.81	993.21	1010.45	997.78	1009.89
20	10	63.47	51.23	55.93	62.78	65.05	57.29	53.33	57.74	66.89	52.90
20	01	614.19	609.40	620.54	604.32	621.78	612.67	616.78	616.64	634.05	612.93
20	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	00	1020.28	1016.64	1020.42	1010.73	1035.93	1022.18	1004.13	1024.07	1009.30	1018.95

21	10	76.83	74.82	75.49	69.93	70.36	72.72	69.72	68.22	71.88	78.61
21	01	637.68	621.42	632.15	631.58	644.40	646.34	627.71	634.52	640.47	652.28
21	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	00	1014.10	1018.82	1009.65	1017.94	1029.42	1021.67	1008.44	1035.88	1018.27	1041.54
22	10	84.09	83.04	67.81	80.08	79.97	81.45	76.85	77.70	77.57	78.91
22	01	635.11	642.39	652.57	639.59	631.88	640.18	634.40	631.36	637.98	643.74
22	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	00	1015.70	1019.27	1012.08	1020.77	1029.08	1021.47	1012.03	1035.58	1026.69	1040.12
23	10	83.51	85.02	68.93	73.30	82.55	87.53	85.78	87.82	81.03	79.22
23	01	650.52	644.51	638.33	642.26	631.39	633.93	644.68	649.63	651.55	633.51
23	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	00	1011.72	1017.36	1017.42	1021.73	1027.57	1023.00	1010.37	1032.78	1030.51	1040.99
24	10	79.50	67.72	81.27	88.70	78.83	86.32	80.68	72.48	86.07	72.80
24	01	630.17	639.22	650.32	657.90	635.85	659.10	629.41	648.82	660.24	647.16
24	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	00	1018.82	1022.57	1017.52	1020.18	1031.94	1018.85	1016.62	1036.56	1026.85	1043.67
25	10	83.40	79.07	89.82	72.43	79.75	82.77	91.59	83.33	74.06	85.83
25	01	660.85	647.23	638.93	644.84	649.51	638.47	632.98	642.06	664.44	640.11
25	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	00	1022.55	1020.92	1017.77	1014.09	1030.38	1025.49	1010.81	1035.33	1020.03	1041.01
26	10	85.80	74.64	76.60	69.86	91.16	85.68	80.63	83.63	85.39	79.79
26	01	649.31	649.80	644.61	637.55	635.53	639.22	638.22	644.89	632.03	646.48
26	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	00	1016.71	1019.19	1023.55	1020.75	1032.55	1022.45	1007.36	1035.73	1026.64	1044.32
27	10	89.58	77.80	88.67	78.91	87.88	94.56	79.84	87.33	82.19	78.82
27	01	632.95	642.17	637.15	629.11	655.77	647.62	629.78	646.20	653.88	648.42
27	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	00	1017.97	1024.60	1017.59	1023.80	1025.36	1022.26	1011.25	1041.66	1024.31	1039.69
28	10	83.20	80.30	82.85	81.89	76.45	86.42	81.06	82.73	83.51	81.63
28	01	646.43	647.55	642.84	635.39	643.59	640.53	641.02	657.10	645.90	644.10
28	11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Prioritization of AGVs

Each AGV manages its path allocation by calling the centralized controller. In the course of allocation requests occurring at the same time, the AGV with lower ID gets priority.

The cell's operation statistics showed a frequent obstruction of AGV heading the following cell due to failed path allocation. This blocked AGV is holding up the cell production for the next workpiece and thus reducing the available workload. This situation gives an idea to prioritize the AGVs based on their blockage generating quality instead of their ID. We created the following priority calculating method for AGVs with failed path allocation:

The base priority is 0 and can be set up to 3. Each of the following conditions increase the priority by 1:

- AGV heading to the cell,
- AGV present in ingress buffer,
- AGV waiting in work area with a finished workpiece operation.

We did three measurement and compare their results for layout 'bbdcfdeeagha' and maximal AGV number was 27:

- without priority calculation (AGV path allocation based on their ID) (P(0)),
- AGV with highest priority gets path first (P(+)),
- AGV with lowest priority gets path first (P(-)).

According to the results there is only a slight (0.1% to 0.5%) alteration on gross time using P(+) or P(-) priority. At the same time there is significant decrease on simulation run speed due to the constant priority calculation. That makes P(+) or P(-) method worthwhile only in case of abundant simulation hardware which capacity cannot be utilized for some other simulation goals.

Number of AGVs

Minimal AGV number = 12 provides a dedicated transport device to feed each cell with necessary workload. Depending on the layout additional AGV increases productivity to a particular level. With activated ingress and egress buffers the optimal AGV number is around 21 and 23. Using higher AGV may not add significant improvement but causes elevated waiting time during path allocation and higher maintenance costs on a real factory. Using a L(R) product list, the layout 'bbdcfdeeagha' shows the following manufacturing time depending as a function of AGV number (Table 6).

Table 6 The manufacturing times as a function of the number of AGVs

number of AGVs	manufacturing time (min)	number of AGVs	manufacturing time (min)	number of AGVs	manufacturing time (min)
12	3412.61	22	2433.79	32	2432.25
13	3187.07	23	2435.21	33	2434.32
14	3004.90	24	2434.34	34	2438.08
15	2851.59	25	2431.66	35	2430.71
16	2725.76	26	2434.32	36	2428.51
17	2624.06	27	2431.01	37	2435.55
18	2547.61	28	2435.64	38	2434.80
19	2493.28	29	2429.30	39	2432.58
20	2463.61	30	2431.08	40	2439.21
21	2438.98	31	2432.99		

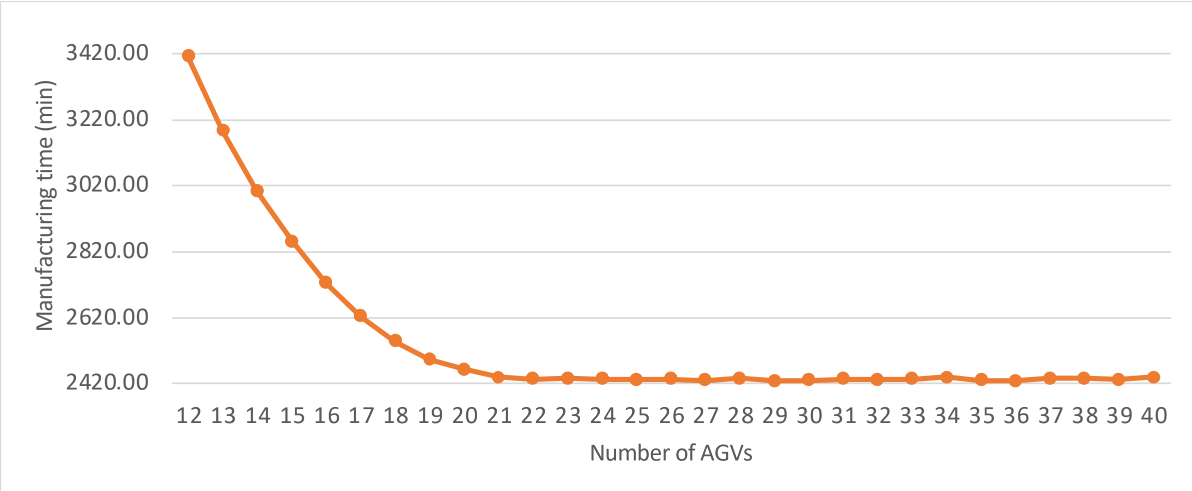

Figure 4 The manufacturing times as a function of the number of AGVs

The columns in Table 7 are as follows: PROD.TIME: time required to produce 3000 products; WORKCNT: average number of products deliver by the AGV during the process; WORKSTEP: average of the sum of loading and unloading times, technical time in AGV-POOL, time spent in production cells per AGV; MOVING: average of material handling time total per AGV; WAITING FOR PATH: average of total route waiting time per AGV; WAITING FOR ROAD: average of road waiting time total per truck; MOVING TIME: total time of AGVs with material handling; WORKING TIME: total time spent by AGVs on work; WAITING TIME: total time spent by AGVs with waiting.

Table 7 Manufacturing process characteristics for different numbers of AGVs

AGV	PROD.TIME (h)	WORKCNT (piece)	WORKSTEP (h)	MOVING (h)	WAITING FOR PATH (h)	WAITING FOR ROAD (h)	MOVING TIME (h)	WORKING TIME (h)	WAITING TIME (h)
12	56.84	250.00	44.74	7.35	0.79	3.90	88.20	536.90	56.27
13	53.15	230.80	41.30	6.81	0.98	4.01	88.57	536.90	64.87
14	50.08	214.30	38.35	6.38	1.17	4.14	89.30	536.90	74.35
15	47.47	200.00	35.79	5.99	1.42	4.23	89.86	536.90	84.76
16	45.46	187.50	33.56	5.64	1.85	4.39	90.25	536.90	99.83
17	43.88	176.50	31.58	5.34	2.42	4.53	90.72	536.90	118.12
18	42.69	166.70	29.83	5.07	3.06	4.72	91.30	536.90	140.10
19	41.79	157.90	28.26	4.83	3.74	4.96	91.68	536.90	165.38
20	41.07	150.00	26.84	4.61	4.38	5.25	92.14	536.90	192.54
21	40.66	142.90	25.57	4.41	5.18	5.50	92.71	536.90	224.41
22	40.55	136.40	24.40	4.24	6.05	5.88	93.24	536.90	262.40
23	40.46	130.40	23.34	4.06	6.88	6.19	93.49	536.90	300.68
24	40.51	125.00	22.37	3.91	7.74	6.51	93.78	536.90	342.05

25	40.49	120.00	21.48	3.78	8.45	6.81	94.49	536.90	381.66
26	40.52	115.40	20.65	3.66	9.19	7.06	95.06	536.90	422.32
27	40.53	111.10	19.89	3.53	9.80	7.35	95.23	536.90	463.12
28	40.52	107.10	19.17	3.43	10.43	7.52	96.02	536.90	502.65
29	40.44	103.40	18.51	3.32	10.90	7.75	96.37	536.90	540.68
30	40.43	100.00	17.90	3.23	11.39	7.96	96.97	536.90	580.35
31	40.30	96.80	17.32	3.16	11.77	8.09	97.90	536.90	615.70
32	40.04	93.80	16.78	3.06	12.01	8.23	98.08	536.90	647.88
33	40.45	90.90	16.27	3.00	12.81	8.41	99.04	536.90	700.38
34	40.12	88.20	15.79	2.93	13.01	8.43	99.76	536.90	729.05
35	39.94	85.70	15.34	2.86	13.31	8.48	100.14	536.90	762.60
36	38.68	83.30	14.91	2.78	12.78	8.26	99.93	536.90	757.44
37	39.64	81.10	14.51	2.73	13.89	8.54	101.15	536.90	830.12
38	38.93	78.90	14.13	2.67	13.77	8.40	101.45	536.90	842.75
39	38.39	76.90	13.77	2.61	13.80	8.26	101.67	536.90	860.18
40	37.16	75.00	13.42	2.53	13.28	7.97	101.10	536.90	850.10

The Table 7 shows no significant decrease in manufacturing time for more than 23 AGVs. Using more and more AGVs causes steadily raising values in ‘waiting for path’ status which is not desired. Scaling AGV number up increases ‘moving time’ since more AGVs allocate need choose more complex and longer path because of the congestion caused by the number of AGV itself.

Production time of the x-th workpiece (1):

$$t_x = \sum_{i=0}^{m+2} \left(t^i_{Pr,x} + t^i_{WP,x} + \sum_{j=0}^{k_i} t^{i,i+1}_{WR_j,x} + t^{i,i+1}_{M,x} \right) \quad (1)$$

Where:

- m is the number of items in the production process list of the x-th workpiece,
- $\boldsymbol{t^i_{Pr,x}}$ is the working time at the i-th point,
- $\boldsymbol{t^i_{WP,x}}$ is the waiting time for the route at the i-th point,
- $\boldsymbol{t^{i,i+1}_{WR_j,x}}$ are the elements of the waiting times for the journey at the i-th point and on the route to the i + 1-th point,
- $\boldsymbol{t^{i,i+1}_{M,x}}$ is the material movement time between the i-th and (i+1)-th points,
- the zeroth point is the AGV-POOL, the first is the ENTRANCE, the (m+2)-th is the EXIT, the (m+3)-th is the AGV-POOL,
- the loading and unloading times were defined as 120s, while the technical time to be spent in AGV-POOL was defined as 60s ($\boldsymbol{t^1_{Pr}}$, $\boldsymbol{t^{m+2}_{Pr}}$,$\boldsymbol{t^0_{Pr}}$).

5 Discussion

Creating a complex production system requires considering several factors and parameters. Searching for the optimal solution, we shall pay regard to factory layout boundaries, financial considerations, hardware resources and computing power limitations. In the section 4, we showed methods and solutions which can help to optimize material handling, product list and cell workload. Some methods give only a slight improvement, whereas others could make high boost on total productivity and pursuing a ‘good enough’ solution instead of the best one can save tremendous resources.

By simultaneously optimizing layout, production sequence, and AGV route selection, we can provide a holistic solution that we have not encountered in the literature search.

6 Conclusions

In manufacturing companies that use Industry 4.0 technology, real-time availability of information continuously provides the current status of orders and resources. Classic line-based assembly is unsuitable for meeting future diversified production requirements while maintaining high economic efficiency. The objective is to maintain the smoothness of the production process while eliminating equal cycle times. Matrix production offers a suitably flexible solution. In our study, we presented the elements of optimal logistics system design through the example of a model factory using custom simulation software.

Focus areas for future development could include: extending the range of stochastic effects considered, reducing the number of constraints, exploring and incorporating algorithmic options for faster runs, leveraging the potential of intra-day rescheduling and re-tooling, extending the model by increasing the size of the production list and the number of production cells.

References

[1] KOREN, Y.: *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*, Hoboken, John Wiley & Sons, 2010. https://doi.org/10.1002/9780470618813.fmatter

[2] REICHWALD, R., STOTKO, C.M., PILLER, F.T.: *Distributed mini-factory networks as a form of real-time enterprise: concept, flexibility potential and case*

studies, In: Kuhlin, B., Thielmann, H. (eds) The Practical Real-Time Enterprise. Springer, Berlin, Heidelberg, pp. 403-434, 2005. http://dx.doi.org/10.1007/3-540-27367-0_27

[3] WAN, J., YIN, B., LI, D., CELESTI, A.; TAO, F., HUA, Q.: An Ontology-Based Resource Reconfiguration Method for Manufacturing Cyber-Physical Systems, *IEEE/ASME Transactions on Mechatronics*, Vol. 23, No. 6, 8310925, pp. 2537-2546, 2018. https://doi.org/10.1109/TMECH.2018.2814784

[4] BÁNYAI, T.: Real-time decision making in first mile and last mile logistics: How smart scheduling affects energy efficiency of hyperconnected supply chain solutions, *Energies*, Vol. 11, No. 7, 1833, pp. 1-25, 2018. https://doi.org/10.3390/en11071833

[5] TANG, D., ZHENG, K., ZHANG, H., ZHANG, Z., SANG, Z., ZHANG, T., ESPINOSA-OVIEDO, J.-A., VARGAS-SOLAR, G.: Using autonomous intelligence to build a smart shop floor, *International Journal of Advanced Manufacturing Technology*, Vol. 94, No. 5-8, pp. 1597-1606, 2018. https://doi.org/10.1007/s00170-017-0459-y

[6] DEMARTINI, M., TONELLI, F.: *Quality management in the industry 4.0 era*, Proceedings of the Summer School Francesco Turco, 2018-September, pp. 8-14, 2018. http://dx.doi.org/10.26524/jms.2018.17

[7] WEYER, S., MEYER, T., OHMER, M., GORECKY, D., ZÜHLKE, D.: Future Modeling and Simulation of CPS-based Factories: an Example from the Automotive Industry, *IFAC-PapersOnLine*, Vol. 49, No. 31, pp. 97-102, 2016. https://doi.org/10.1016/j.ifacol.2016.12.168

[8] IHLENFELDT, S., WUNDERLICH, T., SÜSSE, M., HELLMICH, A., SCHENKE, C.-C., WENZEL, K., MATER, S.: Increasing resilience of production systems by integrated design, *Applied Sciences*, Vol. 11, No. 18, 8457, pp. 1-23, 2021. https://doi.org/10.3390/app11188457

[9] LYCZKOWSKI, E., WANJEK, A., SAUER, C., KIESS, W.: *Wireless Communication in Industrial Applications*, 2019, 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2019. https://doi.org/10.1109/ETFA.2019.8869323

[10] SEIDEL, R., AMADA, H., FUCHS, J., THIELEN, N., SCHMIDT, K., VOIGT, C., FRANKE, J.: *Data Mining System Architecture for Industrial Internet of Things in Electronics Production*, IEEE 26th International Symposium for Design and Technology in Electronic Packaging, SIITME 2020 - Conference Proceedings, 9292282, pp. 75-80, 2020. https://doi.org/10.1109/SIITME50350.2020.9292282

[11] MAY, M.C., SCHMIDT, S., KUHNLE, A., STRICKER, N., LANZA, G.: Product Generation Module: Automated Production Planning for optimized workload and increased efficiency in Matrix Production Systems, *Procedia CIRP*, Vol. 96, pp. 45-50, 2021. https://doi.org/10.1016/j.procir.2021.01.050

[12] ASSADI, A.A., FRIES, C., FECHTER, M., MASCHLER, B., EWERT, D., SCHNAUFFER, H.-G., ZÜRN, M., REICHENBACH, M.: User-friendly, requirement based assistance for production workforce using an asset administration shell design, *Procedia CIRP*, Vol. 91, pp. 402-406, 2020. https://doi.org/10.1016/j.procir.2020.02.192

[13] INDRI, M., LACHELLO, L., LAZZERO, I., SIBONA, F., TRAPANI, S.: Smart sensors applications for a new paradigm of a production line, *Sensors*, Vol. 19, No. 3, 650, pp. 1-36, 2019. https://doi.org/10.3390/s19030650

[14] OSIECZKO-POTOCZNA, K.: Reasons, benefits and challenges on the road to automated internal transportation, *Acta logistica*, Vol. 11, No. 4, pp. 605-613, 2024. http://dx.doi.org/10.22306/al.v11i4.557

[15] WANG, X.K., WU, W.M., XING, Z.C., CHEN, X.Y., ZHANG, T.Q., NIU, H.Y.: A neural network based muti-state scheduling algorithm for multi-AGV system in FMS, *Journal of Manufacturing Systems*, Vol. 64, pp. 344-355, 2022. http://doi.org/10.1016/j.jmsy.2022.06.017

[16] HU, X.Y., YAO, X.F., HUANG, P., ZENG, Z.Y.: Improved iterative local search algorithm for solving multi-AGV flexible job shop scheduling problem, *Computer Integrated Manufacturing System*, Vol. 28, No. 7, 2198, 2022. http://doi.org/10.13196/j.cims.2022.07.025

[17] SAHU, B., DAS, P.K., KABAT, M.R.: Multi-robot cooperation and path planning for stick transporting using improved Q-learning and democratic robotics PSO, *Journal of computational science*, Vol. 60, 101637, 2022. http://doi.org/10.1016/j.jocs.2022.101637

[18] SAEED, R.A., RECUPERO, D.R., REMAGNINO, P.: The boundary node method for multi-robot multi-goal path planning problems, *Expert Systems*, Vol. 38, e12691, pp. 2021. http://doi.org/10.1111/exsy.12691

[19] ZHONG, M.S., YANG, Y.S., DESSOUKY, Y.M., POSTOLACHE, O.A.: Multi-AGV scheduling for conflict-free path planning in automated container terminals, *Computers & Industrial Engineering*, Vol. 142, 106371, 2020. http://doi.org/10.1016/j.cie.2020.106371

[20] HU, Y., YANG, H.B., HUANG, Y.: Conflict-free scheduling of large-scale multi-load AGVs in material transportation network, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 158, 102623, 2022. http://doi.org/10.1016/j.tre.2022.102623

[21] ZOU, W.Q., PAN, Q.K., WANG, L., MIAO, Z.H., PENG, C.: Efficient multiobjective optimization for an AGV energy-efficient scheduling problem with release time, *Knowledge-Based-System*, Vol. 242, 108334, 2022. http://doi.org/10.1016/j.knosys.2022.108334

[22] LI, Z., SANG, H., PAN, Q., GAO, K., HAN, Y., LI, J.: Dynamic AGV Scheduling Model With Special Cases in Matrix Production Workshop, *IEEE Transactions on Industrial Informatics*, Vol. 19, No. 6, pp. 7762-7770, 2023. https://doi.org/10.1109/TII.2022.3211507

[23] FANG, C.C., LAI, M.H., HUANG, Y.S.: Production planning of new and remanufacturing products in hybrid production systems, *Computers and Industrial Engineering*, Vol. 108, pp. 88-99, 2017. https://doi.org/10.1016/j.cie.2017.04.015

[24] KUKA AG: Matrix production: an example for Industrie 4.0, [Online], Available: https://www.kuka.com/en-ch/industries/solutions-database/2016/10/industry-4-0--matrix-production [19 Jan 2020], 2016.

[25] HARDAI, I., ILLÉS, B., BÁNYAI, Á.: *Efficiency improvement of manufacturing and logistic processes in industry 4.0 environment*, 12th International Doctoral Students Workshop on Logistics, Otto-von-Guericke-Universität Magdeburg, Germany, 2019. https://doi.org/10.25673/36893

Review process

Single-blind peer review process.