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IN-PLANT LOGISTICS EFFICIENCY VALUATION USING DISCRETE EVENT SIMULATION

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Abstract

The purpose of this paper is to present an applicable approach for the valuation of in-plant logistics efficiency. Therefore, we developed a time-based efficiency concept that considers all relevant time losses when executing production logistics processes. The occurring delays are captured in real-time using modern auto-ID-technologies. For the valuation and improvement of in-plant logistics efficiency, we propose to use simulation modelling to investigate the cause-effect relations in the production system in advance. Thus, a discrete event simulation model has been constructed to model the workflow of a production system with discrete manufacturing processes and its in-plant logistics processes. The aim of the provided simulation study is to prove the functionality and to verify the applicability of the current approach in business practice.

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Key Words: In-Plant Logistics Efficiency, Efficiency Valuation, Discrete Event Simulation

1. INTRODUCTION

Industrial companies must eliminate waste in manufacturing to become more efficient and to achieve a reduction in costs. As a result, many industrial companies implement efficiency improvement programs and establish well-known lean practices, such as 5S, value stream analysis, continuous improvement, to realise efficient processes in manufacturing. In addition, for a more efficient handling of logistical tasks, many companies rely on common concepts and methods, such as just-in-time (JIT) and/or just-in-sequence (JIS) delivery. Scientific research provides suitable approaches and efficiency metrics to evaluate the efficiency of individual and/or a group of manufacturing facilities adequately [1-4]. Furthermore, the existing literature provides appropriate indicators and performance measurement systems for efficiency assessment of JIT- and/or JIS-deliveries [5-8]. However, a comprehensive efficient order processing requires an additional assessment of the entire internal production logistics processes in terms of efficiency. Therefore, it is necessary to provide a practical approach to capture the efficiency of in-plant logistics. In this context, simulation modelling can be a powerful tool to capture the efficiency of in-plant logistics tasks on a regular basis in business practice. By simulating current in-plant logistics tasks, possible inefficiencies can be easily identified along the entire internal value chain. Appropriate measures to eliminate these inefficiencies can be simulated and compared to the current in-plant logistics efficiency. As a result, successfully simulated efficiency-improving measures can be transferred to reality and implemented in practice. Efficiency-improving action can be repeated until an adequate level of efficiency is achieved. Thus, simulation allows a dynamic investigation of the system's behaviour and it therefore facilitates the implementation of a continuous improvement process. Consequently, it is a useful tool for managers to derive appropriate measures for continuously improving a manufacturing system's efficiency.

Related work has been done by different authors. Chance et al. [9] have shown that simulation can be powerful tool to support production improvement. Moreover, Galbraith and Standridge [10] successfully employed simulation to demonstrate how to transfer a push manufacturing system into a pull system. According to Dewhurst et al. [11] simulation can also be a suitable tool to analyse manufacturing systems and to support manufacturing planning. In addition, Kaban et al. [12] demonstrated how to use simulation to solve job shop scheduling problems. A simulation model to evaluate the performance and the flexibility of manufacturing systems has been provided by different authors [13-15]. Manufacturing system design problems have been solved by several other authors using simulation [16].

In this paper, a feasible and practical approach is presented to evaluate the efficiency of production logistics processes. Therefore, a discrete event simulation model has been developed to model the workflow of a discrete manufacturing system and its in-plant logistics processes. The simulation model was built with ARENA to carry out effective simulation [17]. In addition, the paper provides suggestions for the technical realisation of an automated data acquisition and the implementation of our approach in business practice. A simulation study demonstrates the functionality and applicability of the current approach in practice.

2. VALUATION OF IN-PLANT LOGISTICS EFFICIENCY

2.1 Methodological approach for in-plant logistics efficiency valuation

A widely used approach for evaluating the efficiency in production is the concept of Overall Equipment Efficiency (OEE). The OEE is a metric for the assessment of equipment efficiency and it is used in many companies to increase equipment availability and efficiency. In addition, it is used more frequently to assess the efficiency of entire groups of manufacturing facilities and/or entire production lines [2, 18]. For this purpose, the time losses that occur in production are recognised and deducted from the available production time. Nowadays, the occurring time losses can be easily captured by using highly sophisticated IT-systems, such as Manufacturing Execution Systems (MES). MES are specialised software solutions, which allow to record data at any point in the production in real time. The recorded data can be saved and used for various analyses. MES enable a time-related monitoring of production processes and thus facilitate precise and timely efficiency improvements in the execution of production processes.

Academics and practitioners commonly refer to the term production logistics when referring to all transport, handling, and warehousing activities between the receiving and the shipping area of production facilities. In fact, production logistics processes are necessary to realise the flow of material including all handling and transport activities while executing production. By contrast, warehousing activities do not add any value to the products to be produced, when considering discrete manufacturing systems. Therefore, the current approach is not including warehousing activities when evaluating the in-plant logistics efficiency. Furthermore, general production processes can be differentiated from production logistics processes by considering the processing of products. The in-plant logistics efficiency will be evaluated by capturing all time losses that occur while executing production logistics processes.

The occurring time losses will be subtracted from the total available time for executing in-plant logistics tasks. This results in the productive in-plant logistics time. The determined productive time for processing production logistics processes is assessed in relation to the total time available to determine the efficiency of the production logistics processes. The in-plant logistics efficiency metric ($IPLE$) expresses the productive time as a percentage of the total time available. The efficiency of all production logistics processes of any production system can be calculated by subtracting the sum of all delays that occur during processing of the production logistics tasks from the total time available for the execution of all in-plant logistics processes. Formally, the $IPLE$ for any production system with any given number of internal transport vehicles ($j = 1 \dots n$) can be calculated as follows:

$$IPLE\ [\%] = \frac{\sum_{j=1}^{n} a_j - \sum_{j=1}^{n}(i_j + s_j + e_j)}{\sum_{j=1}^{n} a_j} \cdot 100 \tag{1}$$

In the first step, all idle and downtimes will be deducted from the total time available to determine the maximum feasible time for processing in-plant logistics. Therefore, all planned and unplanned idle and downtimes of the internal transport vehicles are to be considered. The planned downtimes, such as breaks, can be extracted from the work schedule and/or the ERP-systems. Unplanned idle and downtimes are in particular waiting periods that arise, if there is either no request to perform internal transport processes or internal transport vehicles are currently not available. Hence, waiting times primarily occur when the available means of internal transport are underutilised and/or internal transport vehicles are not available to perform transport tasks due to breakdowns. The maximum feasible time for processing in-plant logistics is the difference of the total available time for handling production logistics processes and the sum of the idle and downtimes. In the next step, all speed losses have to be deducted from the maximum feasible time for in-plant logistics. Speed losses in production logistics processes can be attributed to a reduced transport speed. The reduced transport time is determined by deducting the sum of all speed losses from the maximum feasible time for in-plant logistics. In a last step, we have to consider any loss in efficiency caused by empty runs while executing production logistics processes. The efficiency losses due to empty runs are subtracted from the reduced in-plant logistics processing time. This results in the productive in-plant logistics processing time. The ratio of the productive and the available in-plant logistics processing time provides the *IPLE* metric. The following Table I shows how to calculate the productive in-plant logistics processing time.

Table I: Calculation of the productive in-plant logistics processing time (Source: Authors).

Total time available for processing in-plant logistics tasks (a)			
–	Planned idle and downtime	(i)	i.e. breaks, etc.
–	Unplanned idle and downtime		i.e. underutilisation, breakdowns, etc.
=	**Maximum feasible time for in-plant logistics**		
–	Speed losses (s)		i.e. time losses due to reduced speed, etc.
=	**Reduced in-plant logistics processing time**		
–	Time of empty runs (e)		i.e. time losses due to empty runs, etc.
=	**Productive in-plant logistics processing time**		

2.2 IT-Infrastructure for automated data acquisition and processing

The *IPLE* metric is a time-based efficiency measure of production logistics processes. A system for a time-related data collection has to be designed to obtain the necessary data for efficiency evaluation. We propose to design a system that allows communication between the products to be processed, the internal transport vehicles, and the MES or ERP-system [19]. This communication ability between objects and information processing systems is part of ubiquitous computing [20]. It is commonly implemented by using so-called smart devices and/or smart labels. Basically, to gain the necessary information for efficiency evaluation it is to ensure that a transport request is triggered after finishing the operations at the individual processing stations. This transport request can be triggered either manually or automatically. An automatic triggering of the transport request may be done, for example, by carrying out a weighing of transport containers or by a digital imaging of fully loaded transport containers. After a transport request has been triggered, it is recorded in a document and the incoming transport requirements are assigned to the available transport vehicles sequentially. In the event that several transport requests arrive simultaneously, a prioritisation of the incoming transport requests is made. Furthermore, the availability of a suitable transport vehicle to carry out the transfer order will be checked by the time-related data collection system. A lack of transport vehicle availability will lead to the effect that the transport request will wait until a vehicle is available to execute the transfer order. The following Fig. 1 illustrates an activity diagram of the in-plant logistics control system.

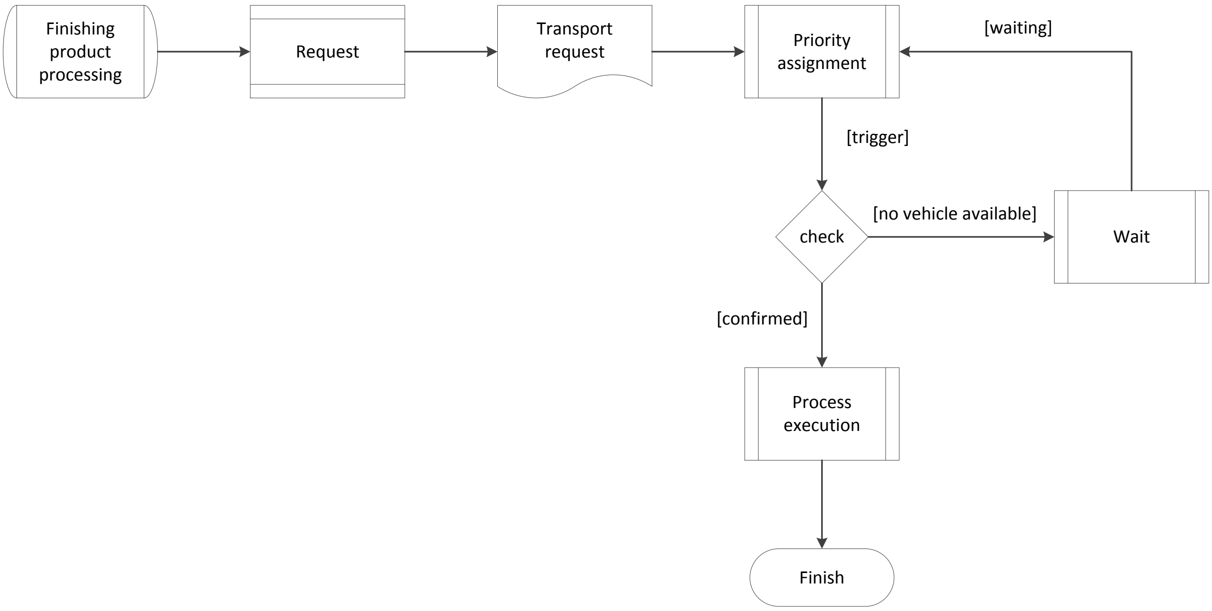

Figure 1: Activity diagram of an in-plant logistics control system (Source: Authors).

The transport containers can be equipped with Radio Frequency Identification (RFID) tags to detect the transport times, the idle and downtimes, the speed losses, and the time losses due to empty runs. The information retrieval for subsequent efficiency assessment is carried out by RFID antennas [21]. For this purpose, it is necessary to provide the processing stations of the production system with mid- or wide-range (M/W-R) antennas. Additionally, the internal transport vehicles have to be equipped with ultra-low-range (UL-R) antennas. The UL-R antennas capture the start time of the internal transport process when taking the container on the transport vehicle. The end point of the internal transport process is recognised when the relevant RFID tag leaves the frequency range of the UL-R. The actual transport time without the time for loading and unloading at the processing stations is recorded by the M/W-R antennas. The physical transport of the products begins when leaving the frequency range of the M/W-R antenna of the source station and ends upon arrival in the frequency range of the M/W-R antenna at the destination station. As a result, the loading and unloading time can be determined by comparing the time records of the UL-R and the M/W-R antennas. The time losses due to reduced transport speed can be recognised by deducting the recorded transport time from the previously planned transport time. The planned transport time is calculated from the transport route and the required transport speed. Finally, the empty runs have to be determined. The empty run time is the time between the confirmation of the transport request and the start time of the internal transport process, which is captured by the UL-R antennas of the transport vehicles. Fig. 2 below illustrates the technical detection of the transport time and the occurring time losses while executing in-plant logistics tasks.

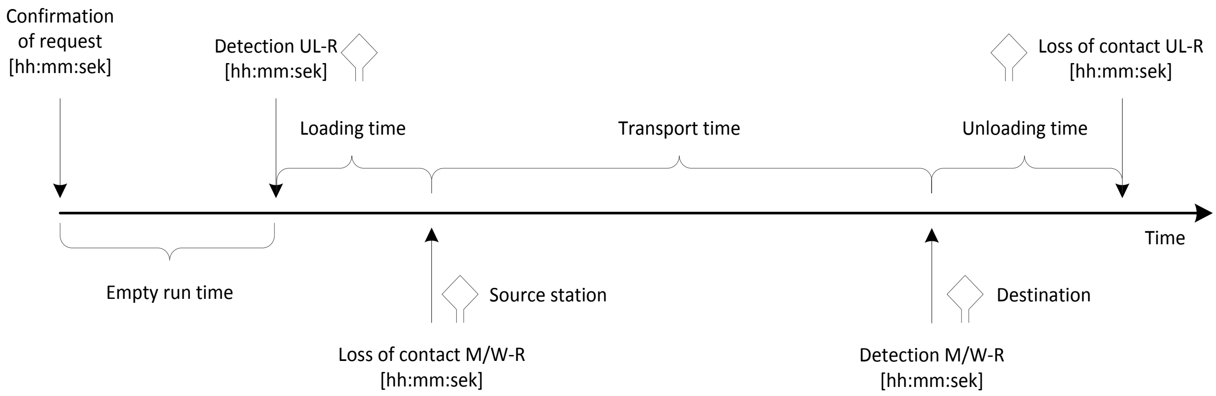

Figure 2: Technical detection of the transport time and the time losses (Source: Authors).

3. SIMULATION STUDY FOR IN-PLANT LOGISTICS EFFICIENCY VALUATION IN DISCRETE MANUFACTURING

3.1 Objectives of our simulation study

Simulation is a commonly accepted tool in improving manufacturing facilities and processes [12-16]. Discrete event simulation (DES) is very accurate and it can capture virtually any level of production detail. DES can recognise both time-dependent and random behaviour and in most cases it helps to understand how a specific system works [9]. Logistical problems are often visualised by using computer models [22]. For this paper, the functionality and applicability of our approach to evaluate in-plant logistics efficiency is demonstrated by using simulation. This is because simulation provides a dynamic view on a system's mechanism and it additionally explains mutual dependencies of different system elements. Hence, the main objective of our simulation study was to investigate production logistics processes in terms of efficiency and to gain the necessary information for in-plant logistics efficiency valuation.

3.2 Modelling the workflow of a discrete manufacturing system

A DES model has been developed to model the workflow of a production system with discrete manufacturing processes and its in-plant logistics processes. In the current case, the evaluated discrete manufacturing system is deployed to produce sophisticated and high-quality components for medical and optomechatronic systems. Production is currently carried out by fulfilling a production schedule based on sales forecasts. The simulation model was built using ARENA 14.5. Our discrete manufacturing system consists of ten processing stations, which are operated by two internal transport vehicles. Three different product variants (A, B, C), requiring a different number of processing steps $(10, 8, 9)$, are produced in our simulation model. The processing of three different product variants requires a set-up process at the processing stations 4 and 5. There is a four minutes set-up procedure at the drilling station and a 3.6 minutes set-up at the barrel finishing. After processing the products a transport request is triggered and the products are waiting to be transported to the next station. The products are stored in the warehouse after final assembly and packaging of the finished products. Fig. 3 shows the manufacturing environment and the arrangement of the processing stations.

A non-terminating simulation was chosen to carry out the simulation study because we expect statistically more significant and more realistic results. Moreover, to make sure that our results are statistically significant, we decided to choose a start-up period of 480 minutes.

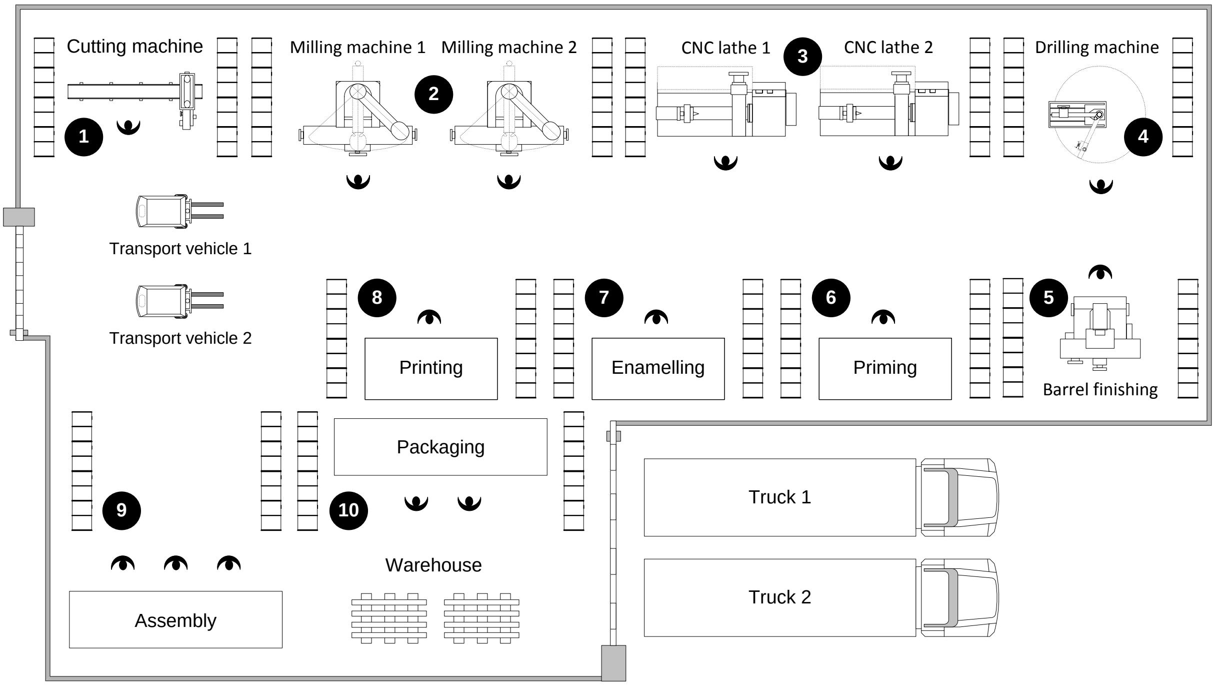

Figure 3: Manufacturing environment and processing stations (Source: Authors).

The Tables II and III show the processing sequence of the different product variants. In addition, the average processing times of the semi-finished products.

Table II: Processing sequence of the product variants (Source: Authors).

Processes / Products	*P1*	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*
A	1	2	4	3	5	6	7	8	9	10
B	1	3	2	3	6	7	9	10	-	-
C	1	3	4	5	2	6	8	9	10	-

Table III: Average processing times [min.] (Source: Authors).

Processes / Products	*P1*	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*
A	6.04	11.30	6.75	13.80	7.04	5.84	14.53	8.15	18.33	5.93
B	4.35	3.84	12.90	5.15	6.16	12.66	15.60	12.30	-	-
C	5.14	6.26	5.19	5.37	4.31	4.83	5.82	17.57	10.32	-

Table IV provides an overview of the characteristics of our simulation study.

Table IV: Overview of underlying system characteristics (Source: Authors).

System elements	Description	Characteristics
Entities	Product *A* Product *B* Product *C*	50 % 30 % 20 %
Resources	(1) R_Cutting (2) R_Milling (3) R_Lather (4) R_Drilling (5) R_Barrel_finishing (6) R_Priming (7) R_Enamelling (8) R_Printing (9) R_Assembly (10) R_Packaging	1 2 2 1 1 1 2 1 3 2
Internal transport	Number of transport vehicles Velocity of transport vehicles	2 83.3 m/min.
Input variables	Time between arrivals Average processing times Shift duration Break	EXP 7.50 min. Table III 480 min. 60 min.
Number of replications	50	
Start-up period	480 min.	
Replication length	9,600 min.	
Type of simulation	Non-terminating simulation	

Table V shows the distance matrix of the internal transport routes in meters.

Table V: Distance matrix (Source: Authors).

	Start	1	2	3	4	5	6	7	8	9	10	End
Start	-	56	-	-	-	-	-	-	-	-	-	-
1	56	-	26	34	18	22	48	52	58	46	58	-
2	62	26	-	6	34	32	36	48	56	44	56	-
3	68	34	22	-	20	22	28	36	42	32	44	-
4	74	20	28	22	-	12	36	38	46	34	48	-
5	74	24	32	24	14	-	24	40	48	36	50	-
6	84	42	36	26	34	24	-	18	24	18	28	-
7	84	48	40	28	38	28	16	-	16	22	30	-
8	90	52	46	36	42	34	24	16	-	26	36	-
9	80	42	36	24	32	24	22	20	24	-	28	-
10	94	56	48	36	46	36	32	28	38	28	-	54
End	130	92	84	72	82	74	68	66	72	64	54	-

3.3 Simulation results and in-plant logistics efficiency valuation

The results of our simulation show that for the production of product *A* a longer lead time is needed than for product *B*. The longer lead time of product *A* results from a higher number of production processes. Additionally, the total processing time for product *A* is longer. Table VI provides the average processing, waiting, transport, loading and unloading times as well as the work in progress of our simulation study.

Table VI: Average throughput times and work in progress (Source: Authors).

	Product *A*	**Product *B***	**Product *C***
Processing time [min.]	103.19	75.96	73.94
Waiting time [min.]	140.14	110.99	139.30
Transport time [min.]	3.91	3.22	3.86
Loading and unloading time [min.]	5.50	4.50	5.00
Throughput time [min.]	**252.74**	**194.66**	**222.11**
Work in progress [pcs.]	**16.96**	**7.89**	**6.02**

The utilisation of the processing stations and the waiting queues that result from the handling and the transport of the products are shown in Table VII. The resulting waiting queues are primarily determined by the number of available transport vehicles. The increasing utilisation of transport leads to an increasing number of products waiting for transportation. By contrast, a lower utilisation of transport leads to the fact that there are an increasing number of products waiting at the processing stations. As a result, the processing stations are utilised to a higher degree.

Table VII: Summary of simulation results (Source: Authors).

Processing stations	∅ *WTP* [min.]	∅ *NWP* [pcs.]	∅ *WTT* [min.]	∅ *NWPT* [pcs.]	Utilisation [%]
Cutting	24.96	3.36	1.22	0.16	81.92
Milling	5.48	0.73	1.24	0.16	79.44
Lather	8.05	1.41	0.81	0.14	82.88
Drilling	19.88	1.87	0.97	0.09	86.36
Barrel finishing	13.83	1.30	0.82	0.07	88.82
Priming	8.89	1.20	0.81	0.10	87.59
Enamelling	4.20	0.45	0.89	0.09	84.35
Printing	4.01	0.37	1.24	0.11	79.83
Assembly	4.29	0.57	0.84	0.11	88.30
Packaging	7.33	0.99	1.27	0.17	89.45

Transport vehicles			
Name	Number of units	Velocity [m/min.]	Utilisation
Cart	2	83.3	85.07 %

Abbreviations: ∅ Waiting time for processing (∅ *WTP*) ∅ Waiting time for transportation (∅ *WTT*) ∅ Number of waiting parts (∅ *NWP*) ∅ Number of waiting parts for transportation (∅ *NWPT*)

The simulation study aimed at detecting the time losses while executing production logistics processes and at gaining the necessary data for in-plant logistics efficiency valuation. The time available for handling production logistics processes is 480 minutes per shift *(S)*. In this case, the planned downtime corresponds to the break of 60 minutes. Our simulation shows that the internal transport vehicles are utilised up to 85.07 %. The summarised waiting period due to underutilised transport vehicles ($\sum_{j=1}^{n} j$) is 2,866.40 minutes throughout the entire simulation runtime *(SRT)*. This results in a maximum feasible time for processing production logistics processes of 13,933.60 minutes. The speed losses while executing the in-plant logistics tasks were recorded by simulating two different scenarios. In the first scenario, the products were transported with an average speed of 83.3 m/min. In the second scenario, the average transport speed decreases to 60 m/min. As a result, we recorded a speed loss of 78.31 minutes per S and a total of 3,132.40 minutes. Thus, the reduced in-plant logistics processing time is 10,801.20 minutes. Finally, the empty runs were determined empirically by visualising the transfer processes. Our observation has revealed that around 44 % of all internal transport processes represent empty runs. This results in an empty run time of 4,752.40 minutes throughout the entire *SRT*. Consequently, the productive in-plant logistics processing time of our simulated manufacturing environment is 6,048.80 minutes.

Table VIII provides the recorded time losses and illustrates the calculation of the productive in-plant logistics processing time.

Table VIII: Calculation of the productive in-plant logistics processing time (Source: Authors).

In-plant logistics efficiency	***S* [min.]**	***SRT* [min.]**	**$\sum_{j=1}^{n} j$ [min.]**
Total time available for in-plant logistics tasks (a)	480.00	9,600.00	19,200.00
– Planned idle and downtime (i)	60.00	1,200.00	2,400.00
– Unplanned idle and downtime (i)	71.66	1,433.20	2,866.40
= **Maximum feasible time for in-plant logistics**	**348.34**	**6,966.80**	**13,933.60**
– Speed losses (s)	78.31	1,566.20	3,132.40
= **Reduced in-plant logistics processing time**	**270.03**	**5,400.60**	**10,801.20**
– Time of empty runs (e)	118.81	2,376.20	4,752.40
= **Productive in-plant logistics processing time**	**151.26**	**3,024.40**	**6,048.80**

At this point, we can calculate the *IPLE* of our simulated manufacturing environment by using the recorded delays while executing in-plant logistics tasks. The *IPLE* is calculated as follows:

$$\boldsymbol{IPLE}\,[\%] = \frac{19{,}200.00 - 13{,}151.20}{19{,}200.00} = \frac{6{,}048.80}{19{,}200.00} = 0.3150 \cdot 100 = \mathbf{31.50}\,\% \qquad (2)$$

The results show that the in-plant logistics efficiency degree of our simulated manufacturing environment is around 32 %. Our investigation indicates that *IPLE* is suffering from major time losses due to empty runs and reduced transport speed in this case. As a result, efficiency-improving measures should primarily focus on achieving a better match of two-way internal transport routes. A better match of the two-way internal transport routes can be achieved by a more flexible routing. This can be realised by using flexible manufacturing cells. Greater routing flexibility leads to an increasing number of possible production routes [23]. An increasing number of possible routes in production leads to an improved ability to carry out two-way internal transports. Furthermore, adjustments to the sequencing rules may result in a better match of two-way internal transport routes. A modified dispatching of production orders can lead to the effect that two-way internal transport routes can be realised more often. This lowers the number of empty runs when carrying out internal transport. In addition, the internal transport routes must be designed in a way that consistently high transport speed and delay-free transport processes can be ensured. This is closely related to the layout of the production facility. The production layout in terms of internal transport routes can be improved by using tools such as workflow and/or relationship diagrams, etc. As a result of layout improving measures, highly-frequented work stations are closely located to each other. Moreover, an enhanced production layout lacks of crossing areas and/or intersections. Layout improving measures facilitate a faster transport with less delay. This leads to an increasing productive time and a more efficient processing of in-plant logistics tasks. A higher *IPLE* combined with a high *OEE* allows a more efficient handling of customer orders and helps to reduce costs.

4. LIMITATIONS AND CONCLUSION

It could be critically acknowledged that a simulation model is always an abstract representation of reality and therefore a relatively low level of detail can be described. Consequently, all results of a simulation must be checked for plausibility. Furthermore, it is very difficult to capture randomly and non-predictable incidents within a simulation. These random incidents can lead to significantly different simulation results [17]. However, in this case, a simulation study is an appropriate tool to demonstrate the functionality of our approach and its applicability in business practice. It provides a dynamic insight into the mechanism of an in-plant logistics system and it explains the interdependencies of individual system elements. Additionally, the results to be achieved by simulating production logistics issues can be transferred to reality relatively easy in most cases. Another major advantage of simulation is that it allows time-related investigation of the system's behaviour.

Realised *IPLE* is evaluated in the simulation model by capturing the delays while executing production logistics processes. The recorded delays will be subtracted from the total time available for processing in-plant logistics tasks. The total available time represents a variable that has to be accurately planned for every single in-plant logistics system. In the present application, the difference between the total available time and the maximum feasible time for processing in-plant logistics tasks may not be exclusively seen as a loss of availability. A loss of availability only occurs, if internal transport vehicles are currently unavailable due to breakdowns and there is no replacement to be employed to execute transportation. In most cases, the idle and downtimes might result from missing transport requests, i.e. an underutilisation of transport vehicles. Moreover, it might be challenging to recognise the speed losses while executing production logistics processes. In business practice, the speed losses can be appropriately captured by comparing an average required transport speed to the actually realised average speed of transport. Finally, the empty run times have to be captured to evaluate the *IPLE*. For this case, we observed the visualised transport processes to obtain the number of empty runs for further efficiency evaluation. In the practical application of our approach, we suggest to record empty runs manually and/or by RFID- or other sensor technology.

Further research particularly focuses on the development of a suitable approach to capture a system's entire efficiency holistically. Therefore, a comprehensive approach is necessary to realise a real-time information and data acquisition. This will allow a precise and timely efficiency evaluation along the entire internal value chain. Additionally, further research may concentrate on including warehousing activities, e.g. inventory and/or work in process (WIP), when evaluating the efficiency of entire manufacturing systems.

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