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# Scheduling Charging Operations of Autonomous AGVs in Automotive In-House Logistics

***Einplanung der Ladeprozesse autonomer Transportsysteme in der Intralogistik***

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**Abstract:** Scheduling approaches for the charging of Automated Guided Vehicles (AGVs) are based on three key components: the timing of charging processes, the selection of a charging station and the duration of the charging process. Based on literature research introduced in this paper, two scheduling approaches have been studied: a rigid approach, based on state-of-the-art solutions, captures the optimal case for a single AGV. A flexible approach, particularly focusing on autonomous behaviour of AGVs, aims for an optimum for the whole AGV fleet. Therefore, the concept of auction-based task allocation is transferred. A closed-loop simulation compares both scheduling approaches for the application of automotive in-house logistics. The flexible approach shows a higher scheduling effectiveness, although influenced by the charging station allocation.

## 1 Introduction

The increasing individualisation of products requires flexible production systems including innovative logistics systems. For in-house logistics, this implies that rigid conveyor technology is replaced by adaptable and connected systems to control the increasing complexity and dynamics. Therefore, the organisation of material flow in production plants is decentralised, which enables autonomously acting entities to control themselves for the execution of transport tasks. In the vision of „Logistics 4.0" , vehicles are cooperating in self-learning systems, exchanging information and making decentralised decisions supported by artificial intelligence (Hompel 2010; Günthner et al. 2012; Hompel and Henke 2014).

Improved navigation by laser and sensor techniques has made it possible for AGVs to move freely, avoid obstacles and handle material by themselves (Ullrich 2015). Given this technological progress, autonomous AGVs are taking a key role in future in-house logistics within automotive plants. One example among many others is the smart transport robot (STR) that was developed in a cooperation between the BMW Group and the Fraunhofer Institute for Material Flow and Logistics. This vehicle is deployed in supply logistics for production and assembly in BMW plants, shown in Figure 1 (BMW 2016).

Autonomous AGV-systems, organised by decentral control, are facing challenges concerning charging activities (Oliveira et al. 2011). While scheduling of charging activities for small systems with only a few vehicles seems to be trivial in the first place, scheduling operations for large-scale systems turn out to be much more challenging. Decisions regarding location, duration and timing of battery charging for hundreds of AGVs, sharing several charging stations, gain importance to ensure well-functioning charging processes. Charging processes are scheduled and performed dynamically during system operations without endangering the running production. If charging activities are not scheduled properly, bottlenecks for the availability of AGVs occur and system efficiency declines (Kabir and Suzuki 2018b). Due to the dynamic behaviour of in-house logistic systems, scheduling approaches are evaluated through simulation-modelling.

## 2 Related Literature and Scientific Contribution

Three key components of a scheduling approach were identified by reviewing the related literature: timing of the charging process, selection of the charging station and the duration of charging processes. Table 1 compares scheduling approaches of several studies on battery charging. Timing is mostly proposed to be based on charge-thresholds (Zou et al. 2018; Kabir and Suzuki 2018a, 2018b) and opportunities between transport jobs (Ebben 2001; Zou et al. 2018). Kawakami and Takata (2011) determine the timing of charging operations in a way to minimise battery deterioration. The selection of a charging station is mostly facilitated by heuristics, like choosing the nearest station (Ebben 2001; Kabir and Suzuki 2018b). Different heuristics are compared by Kabir and Suzuki (2018a), whereas two studies do not consider this selection criteria (Kawakami and Takata 2011; Zou et al. 2018). The duration of a charging operation is usually determined by the time it takes to swap a battery or by fully charging it. Also, a charge-threshold is applied by Kabir and Suzuki (2018b), and handling time is utilised by Zou et al. (2018) for charging during jobs.

***Figure 1:*** *BMW's smart transport robot at the BMW plant in Regensburg*

***Table 1:*** *Comparison of scheduling approaches in the literature*

| Scheduling Component | Ebben (2001) | Kawakami & Takata (2011) | Zou et al. (2018) | Kabir & Suzuki (2018a) | Kabir & Suzuki (2018b) |
|---|---|---|---|---|---|
| Timing | Opportunity/ charge range | Min. battery deterioration | Opportunity/ threshold | Threshold | Threshold |
| Selection | Nearest | - | - | Heuristics | Nearest |
| Duration | Swap time | Swap time | Handling time / full | Swap time | Full / threshold |

Present approaches mainly pay attention to the currently considered vehicle. For example, a vehicle's decision on whether to choose the nearest charging station or a different one only depends on its own state of charge. The point in time a vehicle occupies a charging station is only determined by the time it takes to charge its own battery to maximum level of charge (Kawakami and Takata 2011, Zou et al. 2018, Kabir and Suzuki 2018a, Kabir and Suzuki 2018b). However, to achieve an efficient overall system in autonomous AGVs, vehicles communicate with each other to find compromises and try to achieve an optimum together. AGVs would consider the occupation of stations by other AGVs, their state of charge and would, based on this information, collectively determine a vehicle's priority for charging. Therefore, a flexible scheduling approach that considers multiple autonomously acting entities in a dynamic environment is required.

# 3 Methodology

Two scheduling approaches are provided in this study: one rigid approach based on common methods and one flexible approach, developed for autonomous AGV-systems. Both the rigid and the flexible approach consider all of the components for scheduling charging operations identified in the literature review.

## 3.1 Scheduling Approaches

To observe and compare differences in scheduling effectiveness, a simulation model was developed. The following describes the simulation model, followed by the experiment framework and the results.

### *3.1.1 Rigid Scheduling Approach*

The rigid scheduling approach combines the most applied scheduling methods introduced in Table 1. For timing of the charging process, a threshold level for the state of charge is considered. For example, falling below 10% of charge triggers charging operations, as soon as current transport jobs are finished. The nearest available station is selected and charging is carried out until the battery has reached 100% level of charge. If an available station is not vacant, a parking space serves as waiting zone. As a result, an AGV only pays attention to its own state and does not consider its environment. This approach is easily replicable, applicable and ensures a robust process for systems, with sufficient charging stations and replacement vehicles.

### 3.1.2 Flexible Scheduling Approach

The flexible approach developed by the authors includes common methods, which are suggested in the introduced literature and methods transferred from correlated research. Timing of charging operations is organised by two common criteria: (1) the opportunity of idle time is utilised during periods when transport jobs are not given and (2) a superordinate threshold level of 10 % battery charge applies that ensures that sufficient charge remains for approaching a charging station.

The selection of charging stations is based on auctions, a concept used for the allocation of tasks among autonomous vehicles. In this concept, tasks are published to agents, which send an offer for accomplishment, calculated based on an objective function. The best offer is accepted by the auctioneer, who assigns the job to the respective agents (Schwarz 2014). Consequently, charging of AGVs corresponds to such tasks, for which offers are sent from charging stations to the requesting vehicle as a selection criterion. The proposed function for calculating offers is given by Equation 1, which is based on the proposed objective functions by Schwarz (2014).

$$C_{XA} = D_{XA} + O_x * CO + R_x * \left(1 - (BC_B - BC_A)\right) * CBC \quad (1)$$

$A$ indicates the requesting vehicle and $B$ a potentially competing vehicle that either already occupies the station or has reserved it. A reservation is defined by a vehicle that is on its way to the station. The result $C_{XA}$ denotes hypothetical costs if vehicle $A$ selects station $X$, which must be minimised. Three hypothetical cost factors are considered: distance, occupation costs and costs for the difference of battery charge among the competing AGVs. Distance costs are given by the distance $D_{XA}$ between station $X$ and vehicle $A$ in m and represent unfavourable additional consumption of battery charge while driving there. The binary variable $O_x$ owns the value 1, if the station is currently occupied by $B$ and 0, if it is only reserved or available. Correlated occupation costs $CO$ represent time-consuming effort for entering and leaving a station. On the contrary, the binary variable $R_x$ owns the value 1, if the station is currently occupied or reserved by $B$ and 0, if it is available. The variables $BC_A$ and $BC_B$ denote the current level of charge in percent for both vehicles and the parameter $CBC$ relates battery charge to costs. Generally, $A$ should be preferred to $B$ if significantly less charge remains for $A$ than for $B$. By subtracting the difference of charge from 1, high differences are rewarded with low costs and small differences are punished with high costs.

This function is calculated within an algorithm that iterates through a list of charging stations, ordered by ascending distance to vehicle $A$. Costs are calculated for each station until the first available station is found, as its offer cannot be surpassed by subsequent stations. Finally, the station with the lowest costs among the considered will be selected. Further assumptions are required to ensure reasonable auctions: Vehicle $A$ must have a level of charge less than 60% to be allowed to consider occupied or reserved stations. Otherwise the need for charging is assumed to be too low for replacing other charging vehicles. For a release, vehicle $B$ must possess more than 30 % level of charge to be considered as sufficiently charged. Also, there must be a difference in charge between both AGVs higher than 10% to ensure a significant difference in their need to charge. If these conditions are not confirmed, only vacant stations are considered for the requesting vehicles charging. Furthermore, the cost parameters $CO$ and $CBC$ must be determined manually based on preferences for system behaviour: $CO$ was set to 100 and $CBC$ to 500, to strictly force high charge differences of AGVs while rather allowing releases if beneficial.

If an AGV is running out of charge but was not able to negotiate a charging station, a parking space serves as buffer until a station is available. The charging duration is determined on the one hand by reaching the maximum level of charge and on the other hand by cancelling the charging operation. A cancelation can be triggered by a transport job or by an auction-caused release. This approach is beneficial for dynamic systems with limited resources, as vehicles cooperate in sharing those.

## 3.2 Simulation Model

To study the scheduling approaches, a simulation model of an AGV-system was created for the material supply of an automotive final assembly line. The model does not represent a specific production plant, rather an abstraction of its characteristics. Thereby, universally applicable conclusions could be drawn without being focused on one particular use-case. The discrete-event simulation software Siemens Plant Simulation 14 was used. In addition, the logistics library developed by the German Association of the Automotive Industry (VDA), was applied to integrate aspects of agent-based simulation.

### *3.2.1 Model Layout*

The model layout, seen in Figure 2, is arranged as a rectangular grid with an x-axis of 250 m and a y-axis of 150 m. The model includes a final assembly line which is divided into seven sub-lines. 25 work stations are installed on each side along each line, which generates 350 stations in total. The warehouse entry and exit points, by which material enters and leaves the system, are located at the bottom of the model. The interfaces and system boundaries are simplified to one position for pick-up and one for drop of material and are not considered in detail. Within the warehouse stations, space for vehicles and amount of simultaneous pick-up and drop operations are unlimited. All other stations represent work stations for material consumption, where there is only space for one vehicle at a same time.

Tracks are bi-directional and allow upcoming traffic. For delivery of material, vehicles do not block the transport track. However, if a second vehicle wants to enter an already occupied station, it must wait on the track, where it is blocking the road in one way. Overtaking is not allowed. For all crossings, the FIFO-rule (first-in-first-out) is followed and disturbance traffic or human interference do not exist. The central parking space for idle vehicles is located at the bottom of the model. The allocation Areas 1, 2 and 3 offer space for charging stations. Area 1 is located near the warehouse, Area 2 includes locations near major pathways and Area 3 includes locations between the assembly lines.

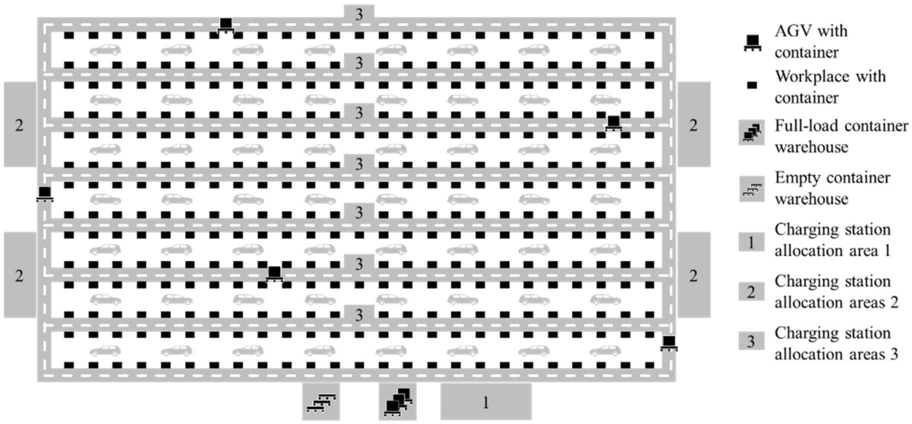


***Figure 2:*** *Model of material delivery to the final assembly line*

### 3.2.2 Deployed Vehicle and Battery

Due to its particular purpose for deployment in an automotive plant, the STR of the BMW Group (BMW 2016) was selected to be modelled. In Figure 1, the STR itself and its transport capacity is illustrated. Space is provided for one load carrier that can either carry one big container or several small ones. Furthermore, the speed of the STR is simplified to 1.5 m/s, both in curves and on straight lanes. The STR contains a lithium-ion battery for energy storage and hence allows rapid and frequent charging processes, while maintaining a high state of health for a long time. These batteries are utilised within the limits 20 % to 80 %, which is simplified in this study: 0 % and 100 % serve as the limits of battery utilisation and deterioration is excluded. It is assumed that batteries are charged linearly and charge is consumed linearly, depending on the current operation.

Four states of operation are defined: idle, handling, driving empty and driving with load. The data regarding battery and charge consumption of the STR is provided in Table 2. The consumption data is estimated based on current technologies and only approximates real data. However, the level of detail is considered as sufficient, as technical characteristics of the STR will vary depending on further developments. To prevent that all AGVs charge at the same time, their initial charge level is uniformly random-distributed when a simulation run is initialised. Batteries are considered to be charged autonomously by approaching charging contacts. Transport processes are not interrupted for charging and vehicles are not allowed to carry load when trying to charge, to prevent bottlenecks in material supply.

***Table 2:*** *AGV battery and charge consumption data*

| Charge consumption | [A] | Battery data | |
|---|---|---|---|
| Idle | 1 | Capacity | 94 Ah |
| Handling | 18 | Charging current | 40 A |
| Driving empty | 4.5 | | |
| Driving with load | 9 | | |

### 3.2.3 System Operations

Transport jobs are generated according to a two-container pull-system that is implemented at each work station to order material from the warehouse if the current container is empty. This process is realised by two separate transportation jobs: one for the full-load delivery and one for the disposal of empty-load. One delivery only includes one container, as the STR's capacity is limited to one load carrier. There is an equal material consumption rate for all work stations without any stochastic numbers. It is set to 30 parts per hour, corresponding the capacity of one container. For a realistic production setup avoiding that all stations order at the same time, the initial stock level at each station was generated random. Only one of the two containers at each work station is initialised as full. The other one is filled based on a uniform random distribution between one and 30. The procedure for transport job allocation follows the disposition rule "nearest vehicle first" (Günthner et al. 2012). Jobs are only assigned to available AGVs and are taken by FIFO-rule from a central job list. The selection of routes for accomplishing a job is based on the shortest way to the destination, calculated exclusively by distance.

The system is operating for 24 hours a day without any breaks or downtime. This is an essential pre-condition for this study, as it is not possible to carry out charging activities only when vehicles are not utilised otherwise. Therefore, charging activities must be integrated within the system operations, in which opportunities occur in between transport jobs. Furthermore, it is assumed that there are no failures for vehicles, work stations or the warehouse. All handling activities last exactly 30s to ensure stable underlying transport processes.

## 3.3 Experiment Framework

The initial number of AGVs was set to 100, which is enough to fulfil the required target throughput of 350 containers per hour, given the assumption that batteries do not need to be charged. We examined suitable parameters for the number of available charging stations to achieve an appropriate throughput in the system and to prevent any bottlenecks in charging capacity. Therefore, we ascertain 40 charging stations for the further experiments, which are distributed equally among selected allocation areas. Having more capacity does not lead to significantly higher throughput as the utilisation decreases. Two experiment steps were defined to be passed:

First, both scheduling approaches are compared by throughput and tested for different allocations of charging stations. A combination of both is defined as a strategy for the subsequent comparison. The throughput is evaluated by the number of full material containers leaving the warehouse per hour. Material delivery and disposal of empty containers are triggered simultaneously and fulfilled one after the other. Therefore, throughput for both processes was equal and hence only full-load deliveries are considered. Second, the numbers of deployed AGVs and charging stations are adapted for each approach to achieve the initial target throughput and to maintain a closed-loop experiment framework. Thereby it is tested how much additional resources are needed for each approach to compensate the charging operations. In detail, the vehicle number was varied between 100 and 160 in steps of 10 and charging stations between 40 and 75 in steps of five.

The simulation run-time was set to one day with 24 hours of continuous operations, as within that time it is possible to recognise whether or not the AGV-system can fulfil the constant demand for material. A shorter simulated-time is inappropriate, as there should be enough time to carry out several charging operations per vehicle to evaluate the scheduling approach. The experiment results are based on average values calculated on three observations per parameter setting, which is sufficient, as only two uniformly distributed random numbers appear: the initial battery charge of AGVs and the initial material stock per work station.

## 4 Simulation Results

The main takeaways of the study are the results regarding the rigid approach (RA) and the flexible approach (FA). Both approaches were compared in different settings. Figure 3 presents the throughput by using both charging approaches in combination with different utilised allocations of charging stations: (1) central locations, (2) major traffic pathways, (3) minor traffic pathways. Even though the differences seem small at the first sight, it is important to consider that throughput is measured per hour. Therefore, a difference of ten units per hour results in 240 more transported containers per day, which is significant and hence justifies the modified y-axis.

In general, two groups of strategies are distinguished in Figure 3: strategies with the rigid approach and those based on the flexible approach. Using the flexible one achieves between 7 and 13 additional containers per hour. On that account, frequent and rapid charging operations by opportunities are beneficial compared to rare, but long charging processes. As a result, enabling vehicles to return quickly after charging is preferred to binding these transport resources in long charging processes during which charging capacity is occupied continuously. Furthermore, different allocations influence the throughput although to a lesser extent. Including Area 1 and 2 is beneficial, whereas Area 3 is not recommended to be included due to the respective distances to charging-stations that AGVs face.

Among the tested charging strategies, there are two strategies that deliver superior results measured by throughput, both including the flexible approach but differ in allocation of stations. For positioning of charging stations, one of them includes Area 1 and the other combines Area 1 (central allocation) and Area 2 (major traffic pathway allocation). The strategy based on the area combination was selected as best-suited strategy for the following reason: the flexible approach

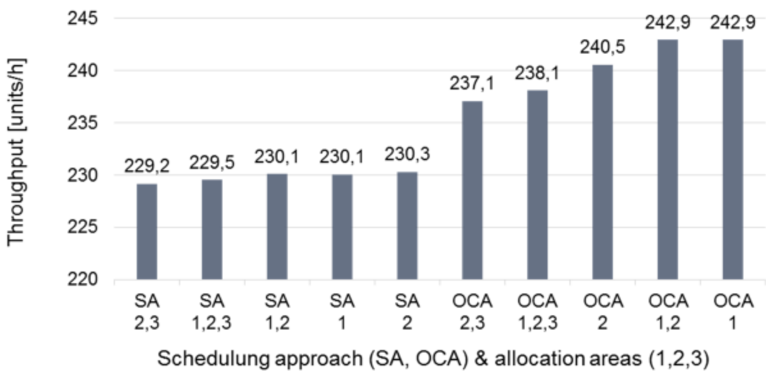


***Figure 2:*** *Throughput for various charging strategies*

***Table 3:*** *Results of parameter experiment for the flexible and the rigid approach*

| Approach | Vehicles | Charging Stations | Throughput [units/h] |
|---|---|---|---|
| Rigid | 150 | 55 | 350 |
| Flexible | 140 | 50 | 350 |

increases the traffic volume by nature as charging processes are started and finished more frequently. For a higher number of vehicles, a concentration of all charging stations near the warehouse was considered too risky for this approach in terms of deadlock prevention. If charging stations are spread over several locations in the layout, the risk of deadlocks due to the additional traffic is reduced.

For the above described flexible approach, as well as for the respective rigid approach, different combinations of the number of vehicles and charging stations were varied to reach the target values while minimising additional resources. Table 3 compares the rigid versus the flexible approach with different parameter settings for numbers of vehicles and charging stations with focus on a throughput target of 350. The result table indicates that combinations with at least 140 vehicles and 50 charging stations are required to approximately reach the target value by using the flexible charging approach. For the rigid approach, 150 vehicles and 55 charging stations are enough to reach the target throughput.

Consequently, in our experiment case, the flexible approach saves 10 vehicles (6.6%) and 5 charging stations (9%) by reaching the same throughout as the rigid approach. The savings can not only be pronounced in acquisition cost, furthermore they are also resulting in higher flexibility of the overall system by using the flexible approach in contrast to the rigid approach.

## 5 Conclusion

This study has focused on approaches for scheduling charging operations of AGV-systems based on the requirements of an automotive plant. Two different scheduling approaches were tested: a rigid approach based on state-of-the-art solutions and the flexible charging approach that particularly focuses on autonomous behaviour of AGVs. A simulation model was designed for the evaluation of the approaches given different allocations of charging stations. The flexible scheduling approach and the allocation of charging stations in proximity to the main process operations is preferred. Thereby charging processes are enabled, which can be triggered spontaneously by AGVs themselves and can be interrupted quickly to react to changing circumstances. As a result, additional vehicles and charging capacity can be reduced and system performance can be increased.

Additional subjects in relation to charging strategies were identified, which are of relevance for further research. However, charging operations can be integrated to a central control unit that includes information from many sources for decisions on charging processes. Further, the design of scheduling approaches and sensitivity for preconditions on charge levels are suggested to be analysed.

Further research might take into account the physical attributes of a battery. For example, the nonlinearity of charging lithium-ion batteries leads to a varying charging duration. Consequently, our method can be improved by integrating this circumstance into Equation (1).

## References

BMW Group Communications Production Network: BMW Group introduces self-driving robots in supply logistics. Company report, BMW Group, 2016.

Ebben, M.: Logistic control in automated transportation networks. Dissertation, University of Twente, Beta Research School for Operations Management and Logistics, 2001.

Günthner, W.; ten Hompel, M.; Tenerowicz-Wirth, P.; Büchter, H.; Schipplick, M.: Algorithmen und Kommunikationssysteme für die Zellurare Fördertechnik. Laboratory report, TU München, Lehrstuhl für Fördertechnik Materialfluss Logistik, 2012.

ten Hompel, M.: Individualisierung als logistisch-technisches Prinzip. In: Günthner, W.; ten Hompel, M. (Eds.): Internet der Dinge in der Intralogistik. Berlin, Heidelberg: Springer 2010, pp. 3-8.

Hompel, M. ten; Henke, M.: Logistik 4.0. In: Bauernhansl, T.; Hompel, M. ten; Vogel-Heuser, B. (Eds.): Industrie 4.0 in Produktion, Automatisierung und Logistik. Wiesbaden: Springer 2014, pp. 615-624.

Kabir, Q.; Suzuki, Y. (2018a) Comparative analysis of different routing heuristics for the battery management of automated guided vehicles. International Journal of Production Research 57 (2018) 2, pp. 624-641.

Kabir, Q.; Suzuki, Y. (2018b) Increasing manufacturing flexibility through battery management of automated guided vehicles. Computers & Industrial Engineering 117 (2018), pp. 225-236.

Kawakami, T.; Takata, S.: Battery life cycle management for automatic guided vehicle systems. In: Matsumoto, M.; Umeda, Y.; Masui, K.; Fukushige, S. (Eds.): Design for innovative value towards a sustainable society. Dordrecht: Springer Netherlands 2012, pp. 403-408.

Klug, F.: Logistikmanagement in der Automobilindustrie – Grundlagen der Logistik im Automobilbau, 2. ed. Berlin, Heidelberg: Springer 2018.

Oliveira, M.; Galdames, J.; Vivaldini, K.; Magalhaes, D.; Becker, M.: Battery state estimation for applications in intelligent warehouses. In: IEEE (Eds.): 2011 IEEE International Conference on Robotics and Automation. Shanghai: 9-13 May 2011, pp. 5511-5516.

Schwarz, C.: Untersuchung zur Steigerbarkeit von Flexibilität, Performanz und Erweiterbarkeit von Fahrerlosen Transportsystemen durch den Einsatz dezentraler Steuerungstechniken. Dissertation, Carl von Ossietzky Universität Oldenburg, Fakultät II - Informatik, Wirtschafts- und Rechtswissenschaften, 2014.

Ullrich, G.: Automated Guided Vehicle Systems – a primer with practical applications, 2. ed. Berlin, Heidelberg: Springer 2015.

Zou, B.; Xu, X.; Gong, Y; Koster, R. de.: Evaluating battery charging and swapping strategies in a robotic mobile fulfilment system. European Journal of Operational Research 267 (2018) 2, pp. 733-753.