Tamás Bódis

Development of order picking algorithms based on product stacking factors

PhD Thesis booklet

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1 Introduction

Warehouses are integrated parts of the global supply chains. Their general function is to support the material supply, the production and the distribution processes from the raw material productions, and the work-in-progress states through to the finished goods. They handle and store products in the storage system and prepare the ordered units for transport. While order picking is the most costly and labour intensive warehousing operation, most of the research works and industrial projects are focusing on this field. The typical decision problems in design and control of order picking processes are the routing methods, layout design, Storage Location Assignment (SLA) methods, order separation, order batching, and zoning. While travelling time is approximately 50% of the whole picking time, the primary goal of the order picking process development is the routing optimisation [9, 4].

Many solutions have been defined for harmonising SLA and routing to decrease the routing distances and times (e.g., [7, 2]). However, while the physical product parameters (dimensions, weight, packaging), the product stacking attributes, and the order characteristics influence the physically possible picking sequence in order to build stable unit loads, researchers rarely take into account these aspects during SLA and order picking routing optimisation. From another perspective, many researchers have attained valuable results in the fields of Pallet Loading and Bin Packing Problem (e.g., [6, 5, 1, 10, 3]), but the solutions are rarely harmonised with SLA and order picking routing algorithms.

The importance of a well sequenced order picking list to support well structured and stable unit loads in order to avoid product damages has already been highlighted [8]. While the developed routing optimisation for this purpose considers product stacking attributes, the solution determined picking sequence of product classes. The algorithm minimises the difference from the defined sequence and minimises the distance but sometimes a more flexible and a more complex sequencing rule definition could be required, which depends not only on the product parameters [8].

If the product location assignment supports the right, risk free picking sequence, the picker will pick the demand on the shortest way without reconstructions. Otherwise the picker has to decide, whether he/she collects products on the right sequence and walks more or picks them with the shortest routing and redesigns the contents of the unit load during the picking. Both solutions can result in the shortest picking lead time. The best choice depends on the length and the content of our list, and on the product allocation in the supermarket. It highlights the impacts of the order characteristics, the departure and arrival position, unit load reconstruction during picking, the routing and the SLA on the sequencing decision of the picker. The general goal of the picker is to minimise the order picking lead time and build stable unit loads without product damages. The order picking system design should synchronise each described decision fields and consider each necessary aspects (e.g, product stacking possibilities) to support the pickers in an effective order picking of different characteristics orders [B6].

2 Research goals and motivation

I realised during industrial projects as a logistics consultant, that the stacking attribute of the packages, and the unit load building possibilities and rules could have a huge impact on the effectiveness of the order picking. Where these aspects are relevant and exact algorithms are not available, the pickers have huge challenges to manage the order picking process. They should take into consideration several factors using their brain to find the shortest picking lead time, to build stable transport units, and to avoid product damages. These challenges are usually handled by best practices in the industry. However, we can realise based on industrial experiences, that synchronisation of the order picking routing, the storage location assignment, and the product stacking attribute based unit load making have a huge impact on the order picking lead time and the operational cost, these aspects have not been discussed and harmonised comprehensively by the order picking research works yet.

Based on my industrial experiences and state of the art research I set my following goals to develop industrially relevant and scientifically unique order picking solutions based on product stacking factors.

- I highlight and define the Order Picking Routing Problem based on Pallet Loading Feature (OPRP-PLF) as a novel and complex problem, and prove its necessity. I define the Pallet Loading Features (PLF), which depends on product attributes, order picking list characteristics, and order picking system.

- I build a formalised, flexible, parametric, and industrially relevant model for the OPRP-PLF. This model should be defined based on known, easily measurable and rarely changing data, because proper product parameters (geometric, weight) are rarely available.
- I develop a methodology for examining, when it is necessary to implement an OPRP-PLF algorithm at a warehouse.
- I examine the complexity of my problem to find the right optimisation methodology.
- I develop, evaluate, and compare algorithms for the OPRP-PLF, which can support the pickers with time effective picking sequence within the available time. The solution should ensure flexibility, avoid product damages, support the stable unit load building, and minimise the order picking lead time.
- I examine the effects of allowing unit load reconstruction during order picking on the order picking lead time.
- I examine the effects of the warehouse layout, the PLF based SLA and routing synchronisation on the order picking effectiveness. I would highlight, that applying PLF aspects during SLA has an impact on the order picking lead time. Defining the right PLF based SLA algorithm is a possible further research, but not the scope of my proposed research.

Besides my research, I would like to apply my state of the art research and my scientific results into education as new challenges, aspects, and solutions of order picking.

3 Dissertation structure and methodology

My proposed research has two main chapters. The State of the Art chapter summarises the state of the art research in the field of order picking and optimisation. The main points of the order picking state of the art research are the routing, the storage location assignment, the layout, the zoning and the order picking list definition, which are connected to my research. The optimisation State of the Art section summarises the relevant optimisation terminologies and methodologies. The own results chapter introduces my own results based on the following structure.

First of all, Section 3.1 defines the OPRP-PLF, explains its influencing factors, and highlights the relevance of the industrial applications. I describe my model for formulating the pallet loading rules by mathematical formulas. This section introduces my methodologies to define the necessity of applying OPRP-PLF algorithms at a warehouse. My solutions can highlight when OPRP-PLF algorithms should be implemented for a warehouse based on the analysis of the pallet loading rules and monitoring the nature of the warehousing processes.

Section 3.2 examines the complexity of industrially relevant sub-problems of the OPRP-PLF based on a mathematical methodology. I determine formula for each case to calculate the possible number of order picking sequencing variations and I examine the behaviour of those in the case of order picking lists whose length and contents are different. The aim of the complexity evaluation is to find the necessary optimisation methodology for the problem.

I explain the details of my own developed algorithms for OPRP-PLF in Section 3.3. I describe my objective function and highlight the necessity of optimisation based on analytic examination of simple examples. I introduce alternative solutions for Bacterial Memetic Algorithm operators and Simulated Annealing algorithms. Pseudo codes and graphics make the solutions understandable and reproducible. The combinations of the mentioned operators will define possible algorithm solutions, which will be evaluated and compared in following section.

Section 3.4 introduces the evaluation of my previously defined possible algorithm alternatives. I examine the algorithms by my own developed computer simulation environment, which is developed for the proposed problem. I evaluate the alternatives by my objective function based on order picking list whose length and contents are different. The aim of this section is to find the relevant algorithms operators and define the algorithm(s) for further application.

Section 3.5 examines the effects of the warehouse layout attributes, the SLA and the unit load reconstruction on the order picking lead time. I determine industrially relevant alternatives for these system attributes to evaluate them on several different characteristics orders by the simulation environment applying the defined OPRP-PLF algorithm(s). Based on the objective evaluation of alternative system configuration I will make consequences on warehousing logistics point of view.

Finally, I summarise my research results and collect my further research.

4 Order Picking Routing Problem based on Pallet Loading Feature - OPRP-PLF

Although the order picking routing and the Pallet Loading Problem are important and usually discussed research fields, my state of the art research highlighted that there is lack of harmonising these fields. The specification of the novel Order Picking Routing Problem based on Pallet Loading Feature (OPRP-PLF) resulted in further solutions for modelling and examining the relevance of OPRP-PLF. The warehouses usually lack of appropriate and up-to-date product attributes (dimensions, weight, stacking attribute, etc.) and well-defined stacking constraints.

Thesis statement 1. *I highlighted that there is a relation and a potential synergy between the order picking routing problem and technological issues like packaging and protection of items. Harmonisation of the order picking routing and the Pallet Loading Problem could be necessary to support the picker in stable transport unit building and avoiding product damages during order picking and transport. I proposed the Pallet Loading Feature and the Order Picking Routing Problem based on Pallet Loading Feature (OPRP-PLF). I defined the Pallet Loading Feature as a logistics system attribute, which depends not only on the product attributes but also on the order picking list characteristics and the order picking system itself.*

Thesis statement 1/a. *I defined a methodology for classifying the order picking lines and formalising the pallet loading rules based on known, easily measurable, and rarely changing information. I defined the Pallet Loading*

Feature based Decision Matrix for formalising the logical picking possibilities of classes.

Thesis statement 1/b. *Since OPRP-PLF is not relevant for every warehouse, I developed methodologies for defining the relevance of applying OPRP-PLF algorithms, which can be used to examine various warehouses. I defined the Pallet Loading Rate based on the evaluation of the Pallet Loading Feature based Decision Matrix and I highlighted the necessity of the order picking process monitoring.*

My publications related to the statement: [B6], [B1], [B5].

5 Complexity of the OPRP-PLF

While the order picking routing algorithms do not consider the Pallet Loading Features, development of algorithms would be necessary for the OPRP-PLF. Algorithm development for novel problems generally should be started with complexity evaluation of relevant industrial cases to define the proper and necessary methodology for optimisation.

Thesis statement 2. *My examination highlighted that meta-heuristics optimisation method is not necessary for OPRP-PLF, when Pallet Loading Class based separated zones are available. However, I proved, that meta-heuristics optimisation method is necessary in the following cases because of the at least exponential growth of the possible order picking sequencing combinations and the low available running time, since the order picking zone is not separated based on Pallet Loading Classes.*

- *Order picking of one unit load without order separation, when unit load reconstruction is not allowed during the order picking.*
- *The order is separated into several unit loads, and unit load reconstruction is not allowed during the order picking.*
- *Unit load reconstruction is allowed during the order picking of one unit load.*

While the picker should get the optimised picking list without wasting time in the daily operation, the algorithm running time is a critical factor. Relying upon these facts, I proposed, that evolutionary optimisation would be one of the suitable meta-heuristics methodologies for the problem.

My publications related to the statement: [B2], [B5].

6 Algorithms for OPRP-PLF

While the algorithm running time is a critical factor of the at least exponential OPRP-PLF, I offer the Bacterial Memetic Algorithm (BMA) for the defined problem, because it has already been successfully utilised in several combinatorial optimisation problems because of its fast convergence speed.

Thesis statement 3. *While the order picking routing optimisation objective functions usually consider the travelling and the picking time, I specified an objective function for minimising the lead time of the OPRP-PLF, which besides those aspects considers the reconstruction time too.*
Based on analytic examination I justified the necessity of the algorithm development, showing that since the shortest route could cause more reconstruction and higher lead time because of the Pallet Loading Feature, hence the picker should be supported by algorithms in the case of complex OPRP-PLF.
I constructed Bacterial Memetic Algorithm (BMA) and population based Simulated Annealing (SA) algorithms for comparing two cases, when reconstruction is avoided (Strict process) and when it is allowed (Non-strict process). I combined the bacterial mutation and the local search operators of the BMA with SA algorithms as a BMA novelty to increase the optimisation efficiency within the short optimisation time.

My publications related to the statement: [B5], [B4].

Figure 1 introduces the defined encoding methods for two cases, when reconstruction is avoided (Strict process) and when it is allowed (Non-strict process).

Table 1 and Table 2 show based on the same picking list that the shorter travel time (T_T) could cause more reconstruction time (T_R) and higher lead time.

Figure 1: Non-strict and Strict encoding methods

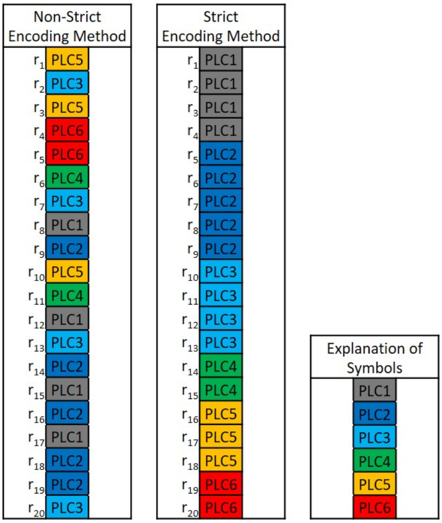


Table 1: Analytic examination **with** reconstruction.

Record	Position	POPC	T_P	r_{r_i}	T_R	S_{r_{i-1},r_i}	T_T	LeadTime
3	Position 3	B	00:10	0	00:00	10	00:06	
1	Position 2	C	00:10	1	00:15	30	00:19	
2	Position 1	A	00:10	2	00:30	50	00:31	
	Start-End					100	01:02	
Sum			00:30		00:45	190	01:58	**03:13**

Table 2: Analytic examination **without** reconstruction.

Record	Position	POPC	T_P	r_{r_i}	T_R	S_{r_{i-1},r_i}	T_T	LeadTime
2	Position 1	A	00:10	0	00:00	100	01:02	
3	Position 3	B	00:10	0	00:00	20	00:13	
1	Position 2	C	00:10	0	00:00	30	00:19	
	Start-End					80	00:50	
Sum			00:30		00:00	230	02:24	**02:54**

7 Algorithm evaluation based on different level of complexity order picking lists

Evaluation of several possible algorithm is usually necessary to define the right concept for a novel problem. I defined possible BMA solutions for OPRP-PLF optimisation based on the possible combinations of my proposed BMA operators. I implemented, evaluated, and compared each BMA and the SA algorithms on the same basis with my computer simulation model. I examined the behaviour of the algorithms on order picking lists with different record numbers.

Thesis statement 4. *Based on the results I proved, that BMA is more effective for the proposed OPRP-PLF than the population based SA algorithm. I concluded, that for most of the applications the strictly initialised, non-strict bacterial mutation, best development local search combined with SA algorithm could be an effective choice.*

Thesis statement 4/a. *I verified, that when the reconstruction time is less than the saved travelling time, then the allowance of reconstruction could result in a lower order picking lead time. However, the non-strict operators are necessary to allow reconstruction but a strict initial population helps with quick improvement.*

Thesis statement 4/b. *I proved, that the Best Development Local Search operators, mainly its SA combined version, perform stably and effectively for both short and long lists.*

Thesis statement 4/c. *I highlighted the operability of applying SA into BMA operators, since the SA combined bacterial mutation and local search operators are competitive with the traditional operators. Mainly the SA combined Local Search operators obtained better results than their alternatives without SA.*

My publication related to the statement: [B4].

Figure 2 shows, that reconstruction (red, initially upper line) could result in a lower order picking lead time.

Figure 2: The SA algorithms result for 20 records order picking list
(horizontal axis: iterations, vertical axis: objective function)

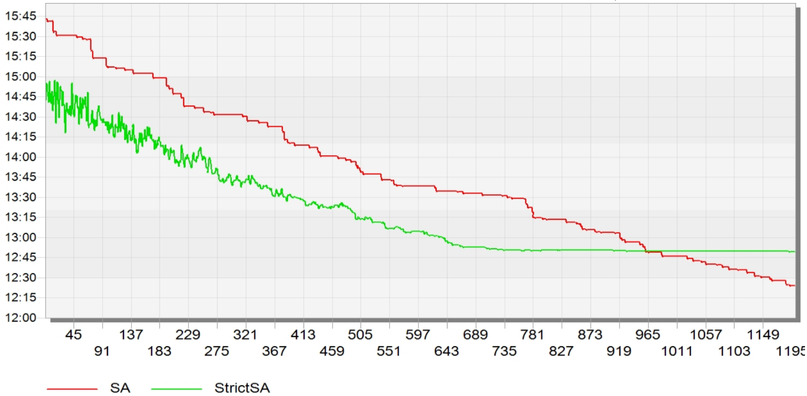
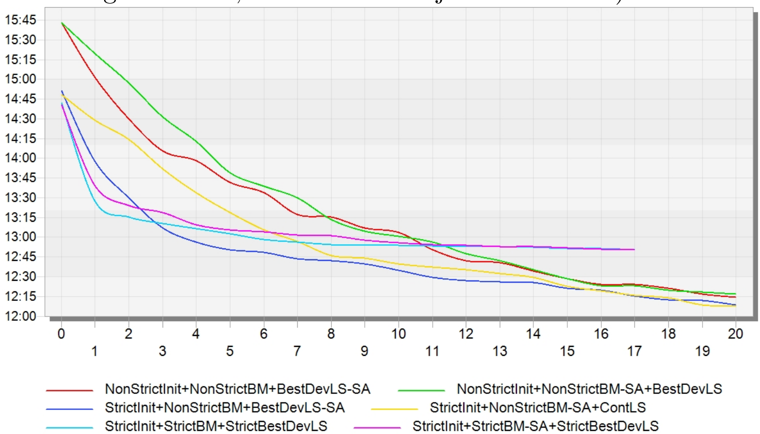


Figure 3 represents that the non-strict operators are necessary to allow reconstruction to reach lower order picking lead time, but the strict initial population helps with quick improvement. The algorithm of the initially upper lines (red and green) applied Non-strict initialisation method.

Figure 3: The best performing combinations of Initial populations and Bacterial Mutation operators for 20 records order picking list
(horizontal axis: generations, vertical axis: objective function)



8 The warehouse layout and the SLA effect on the OPRP-PLF

While several factors influence the warehouse operations, it is necessary to harmonise those factors for the purpose of effective warehousing processes. Relying upon this fact, I examined the effect of the warehouse layout attributes, the Storage Location Assignment (SLA) and the unit load reconstruction on the order picking lead time.

Thesis statement 5. *I proved, that when Pallet Loading Feature is relevant, then Pallet Loading Feature based SLA results in a lower lead time. My simulation results also proved, that allowing reconstruction is necessary for order picking lead time minimisation even in the case of Pallet Loading Feature based SLA because of the order characteristics and the location of the Departure and Arrival position. I verified, that the Departure and Arrival position has an impact on the travelling and reconstruction times in the case of OPRP-PLF, unlike classical routing problems (e.g. TSP).*

My publication related to the statement: [B3].

Figure 4 and Figure 5 illustrate the necessity of the reconstruction and the effects of the Departure and Arrival position based on the same order picking list in the case of Pallet Loading Feature based SLA.

Figure 4: Picking sequence in the case of Non-strict picking, Pallet Loading Feature based SLA, and right sided Departure and Arrival Position

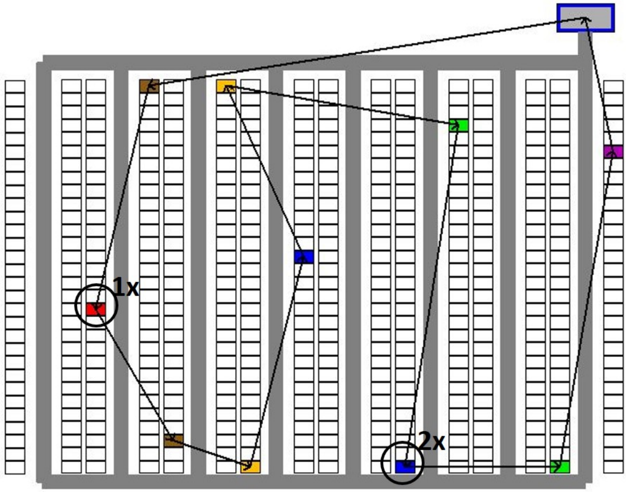
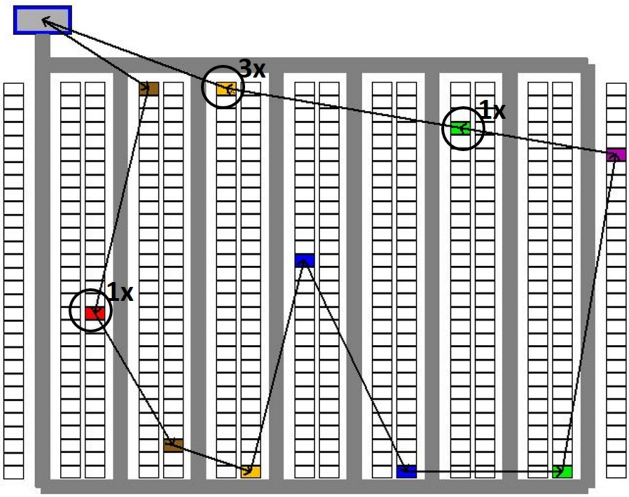


Figure 5: Picking sequence in the case of Non-strict picking, Pallet Loading Feature based SLA, and left sided Departure and Arrival Position



9 Summary and future research

My research highlighted and formalised the OPRP-PLF as a new sub-problem of Order Picking Routing Problem, and developed effective OPRP-PLF algorithms. The developed solutions could provide significant results in supporting the pickers by defining realistic picking sequence within the possible time window. The proposed solutions are important, where the variability of packages, the ordered quantities, and the order picking system itself make the stable unit load building a combinatorially complex problem. The defined BMA algorithm could be integrated into any warehouse management systems (WMS) as routing algorithm. It can also work as a connected external optimisation module triggered by an order picking list via any interface and it sends back the optimised list for the WMS. Besides the advantages and effectiveness of the BMA solution, its sophisticated structure and complex parameter setting requires BMA experienced experts for implementation.

As further research I would like to implement the Special Product and Order Parameter Class (SPOPC) issues into the algorithms to model the system characteristics in a more realistic way. The SPOPC considers the previously picked units and their sequence to define the behaviour of the next record. While my proposed research highlighted the importance of PLF based SLA, it applied previously defined SLA based on logical, manual, and static methodology. I would like to develop SLA algorithms, which will be able to update the SLA based on the actual order characteristics and the position occupation. It would be useful during order picking stock replenishment and storing in processes to find the actually relevant picking or storage position for the products. Although I proved, that applying unit load reconstruction could decrease the order picking lead time, it should be limited to minimise the product damage possibilities in the case of sensitive products. I might apply some fuzzy methodology into the reconstruction procedure. While this work discussed PLF based order picking routing optimisation of one unit load, complementing the algorithm by separating the purchased order for unit loads based on PLF would be a more complex and industrially important problem. The aim of the extended algorithm complemented by order separation should be the minimisation of the lead time of the whole order performing process.

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