XXVII. DEVELOPMENT OF A HEURISTICS FOR A CRITERIA BASED PLANNING OF PALLET STORAGE SYSTEMS

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Abstract

Reproducible and quantitative reasoning as the foundation for high-quality planning processes evolves to be key to achieve high quality of speed for logistical processes. This article strives to fulfill this demand by developing a coherent heuristics for the planning of pallet storage systems.

The heuristics uses quantitative approaches provided by the available literature. In case of nonexistent sources, the missing components are developed and integrated. To be applicable in an industrial environment, the comparison and assessment of the created implementation alternatives is mainly monetary based. The heuristics follows a modular structure to achieve adaptability and extensibility. It explicitly does not intend to replace a human designer but to support him during the creation and assessment of high-quality design alternatives.

A concluding case study evaluates the practical applicability of the heuristics and its created solutions. The review of the heuristics turns out to be positive. As a consequence, extension and improvement tasks are proposed.

1 Introduction

Within the past twenty years logistics has evolved to become a highly regarded business area whose decisions not only affect itself but the whole company. In order to remain competitive it is necessary for any business to develop and implement logistics systems and processes which are able to satisfy the highest standards. Additionally, in a continuously faster growing market the planning and design of such entities is to be repeated more and more often [3]. Hence, the need for higher quality and effectivity in planning has become pervasive. As a foundation for this, quantitative reasoning achieves reproducible designs with objective evidence. In contrast, equipment selection and conceptual design in logistics planning today is largely based on (empirical) knowledge (i.e. design experience) and ad-hoc spreadsheet calculations.

The design of a storage system is a highly difficult task which has already been noted by various authors ([3]; [25]). The rather simple-sounding task of "storing" allows a number of outcomes and requirements that can hardly be overlooked. Storage systems can hold production supplies and finished goods in any shape and number, with requirements to storing high volumes in limited space, reducing labor or investment costs or being able to pick and store goods with very small throughput to name only some of the possible challenges. As well as those, the outcomes of storage systems can vary immensely.

The quantity of literature on storage or warehouse design is large. A comprehensive review focusing on optimization models is given in [2], another more general and up-to-date one in [14]. It can easily be noted that especially the number and diversity of papers which address particular problems by developing formal mathematical models is large ([10]; [17]; [27]). Also, a number of formal design workflows exist which provide a general guideline to follow through the warehouse or storage system design process ([5]; [16]; [22]). The authors of this paper find that between these fields a gap exists which requires to be bridged. While the general workflows only give rough explanations about *what* to do, they do not specify *how* to complete the task [25]. On the other hand, the formal mathematical models address relatively small problems in the overall context of storage design based on a number of assumptions. For practical usage in a design process, their scope appears too small, computational effort too high and they need to be put into a coherent and reasonable order.

The presented paper addresses the need for fast and reproducible design by developing a heuristics that leads through the creation and selection of storage alternatives with an almost fully quantitative foundation. Therefore, it is an approach to close the gap between highly specified mathematical models and general design frameworks. For that purpose, existing models have been evaluated, selected and put into a coherent order. The goal of the proposed heuristics is to achieve a robust design. To specify, a robust design can likely be improved by an experienced designer on the one hand, but on the other hand gives a good solution to start with and a nearly certainly implementable design. As a result, calculations are to be kept simple and rather easily understandable for someone with an engineering background. No specialized simulation or optimization tools should be required and the heuristics is supposed to be easily implementable in a rudimentary programming language. The paper tries to serve as a proof-of-concept to evaluate the use of such a heuristics. Hence, it is limited to one- and two deep pallet storage systems. The equipment options to be implemented were identified beforehand based on frequently implemented designs and material handling market research.

The remainder of this paper starts with a depiction of the current state of the design of storage systems. Afterwards, the general framework of the heuristics is explained.

Section 4 describes the heuristics modules in a more detailed manner. For the evaluation of the applicability of the heuristics, a case study is conducted. The paper concludes with a summary and an outlook to future work.

2 Design of storage systems

As proposed, the design of storage systems is much more difficult than one would think initially. The basic material flow functions of a warehouse as defined by [16] are to receive goods, store goods, retrieve the goods to form customer orders and pack and ship customer orders. Certainly, warehouses are not the only facility within a supply chain which require storing departments. However, none of the other facility types has such a strong focus on the function *storage*, and a good share of the research papers addresses warehouse design as a whole. The storage department in any facility type mainly serves the purpose of synchronizing the points of time of supply and demand [13]. For this, goods have to be *put* into the storage when supplied, *remain* there for a certain time and be *retrieved* when demanded.

[12] define the key aspects of warehouse design (which are therefore treated as valid for storage design) as "the selection and specification of systems to provide the required functionality, the arrangement and staffing of the systems, and the specification of operating protocols". They also note that the size and configuration of the selected technologies need to be specified. Representative for the view of many authors on the current state-of-the-art of warehouse design, [3] state that warehouse design in industrial practice is an *ad hoc* process, hardly formalized and mainly driven by empirical knowledge and experience.

The existing research in the field will successively be categorized in two chapters. First, an overview of various warehouse design workflows is given. Second, we provide a broad look over the huge number of formal mathematical models.

2.1 Warehouse design workflows

Amongst other topics, [5] provide a comprehensive review of various publications which refer to general warehouse design steps. They state that the first attempt of structuring warehouse design was published as early as 1973 by [23]. It consists of three steps, the determination of requirements, design of material handling systems and development of layouts. They further mention a number of fourteen publications which consider formalized warehouse design processes until 2009. Examples for those are ([4]; [7]; [12]; [22]; [28]). The approaches evolve from the mentioned three-steps procedure [22] to more complex and detailed procedures [4] and finally account for the flexible and iterative character of warehouse planning [16]. [5] conclude that all of the authors agree on the following propositions:

- Warehouse design is highly complex;
- The complexity is tackled using step-by-step procedures;
- The steps are interrelated and a degree of reiteration is necessary;

- Due to the high number of possibilities that exist in each step it may be impossible to identify the “optimum” solution.

Based on the existing workflows, [5] develop their own design procedure. They attempt to validate it in cooperation with various companies. Another example for a more up-to-date process for warehouse design is proposed by [18]. He divides the process into different stages of planning with inclining degree of detail. At specified stages, decisions about the preferred alternative have to be made. Another element of the procedure is frequent reiteration of the steps.

Considering the multiplicity of design workflows it becomes obvious that no unique or established procedure for warehouse or storage planning exists. On the contrary, the proposed papers are somewhat similar in their steps and sequence. The creation, assessment and elimination of various design alternatives is mostly part of the papers, as well as the element of reiteration. It has to be noted that even though structured processes are given, a huge amount of expert knowledge is required to perform the steps.

2.3 Formal mathematical models

The amount of formal mathematical models addressing warehouse design problems is large. We consider English- as well as German-speaking literature. We do not intend to provide an exhaustive literature review but depict the current state of research and draw our conclusions from it.

The English-speaking literature on models for warehouse design is well covered in a review of [14]. They provide an overview of 50 papers directly addressing warehouse design problems, an additional 50 papers on travel time models and performance evaluation and 18 papers which cover topics such as benchmarking, case studies and other surveys. Their conclusion on the current quality and applicability of existing research turns out to be negative. Firstly, they state that most of the papers focus on analysis rather than synthesis. Also, only a scarce 10% of papers which directly address warehouse design have been published later than 2000. [14] find that to be highly contrary to the rapid development of computing hardware and solving as well as simulating software. They identify two main reasons for this situation. Firstly, as design decisions are strongly coupled, they cannot be made or modeled in isolation of one another. The scope of a formal analytical (optimization) model which covers all of the necessary decisions appears too large for an individual researcher. Secondly, based on the strong interactions, the demand for total warehouse performance assessment models is huge but their creation a highly challenging task. Their final and maybe most crucial conclusion is that the gap between existing research on warehouse design and its practice is enormous. They find their bridging key for improving state-of-the-art warehouse design methodologies.

While the English-speaking literature provides a huge amount of optimization models, the German-speaking literature on formal mathematical models in warehouse design mainly focuses on the development of formulas which do not optimize but serve well-established and reasonable solutions. In the area of storage capacity calculations [6] builds theoretical foundations at an early point of time. [1] describe a well-established and commonly used approach for capacity calculations for dedicated as well as shared storage operations. [33] uses his own, practically oriented approach in his comprehensive work on storage configuration. The area of cycle time and performance calculation is well covered. [19] provides calculations to determine cycle times for picking operations with manual transportation devices. [29] extends existing approaches to develop an algorithm for performance calculation of various transportation devices. For the cycle time calculation of narrow aisle stackers [9] provides foundations. These are expanded by [8] and [32] for consideration of single and dual cycles. For general usage, the model of [32] was simplified and published in the standard [30]. In this, only single cycles are incorporated. A huge amount of cycle time models for automated storage and retrieval systems (AS/RS) exists. Commonly known are [11] and [31]. [24] published an approach for cycle time calculations in double deep AS/RS. Guidance for dimensioning of storage systems is scarcely published for its own purpose. In [19] a formula for estimation of the optimal number of aisles is published. He gives further suggestions for various dimensioning figures in [20] and [21]. [11] provides a formula for a good length-to-height ratio of racks in AS/RS.

We draw the conclusion that even though the quantity of models is large it requires structuring and targeted further research. The complexity of this topic can be anticipated from the big differences which models for the basically same topic offer. A comparability of the results and assumptions is scarcely given. For the following development of the heuristics a large number of models exists. Still, the planning procedure is not wholly covered.

3 Heuristics framework

The heuristics compares different options of equipment types to identify the one with minimum costs. For that purpose, different equipment alternatives must be considered thoroughly. Considered transportation devices are stacker cranes, narrow aisle stackers and conventional fork lift trucks. The pallets can be stored either cross- or lengthwise in one- or two-deep racks. In case of two-deep racks a row can be single- or mixed article. Stacker cranes which are capable of serving multiple aisles are not considered. The heuristics follows a modular structure to provide adaptability and extensibility. As soon as the calculations indicate that one of the equipment alternatives is not implementable under the given constraints, it is no longer considered as an option. This further reduces the calculation time which cannot be considered problematically anyhow. A component of the heuristics is the optional usage of self-selected calculations by the user. At specified times he can choose between using the proposed calculations or executing his own, and afterwards enter specified parameters to continue with the heuristics. This requires detailed explanation and/or knowledge of how the parameters are defined.

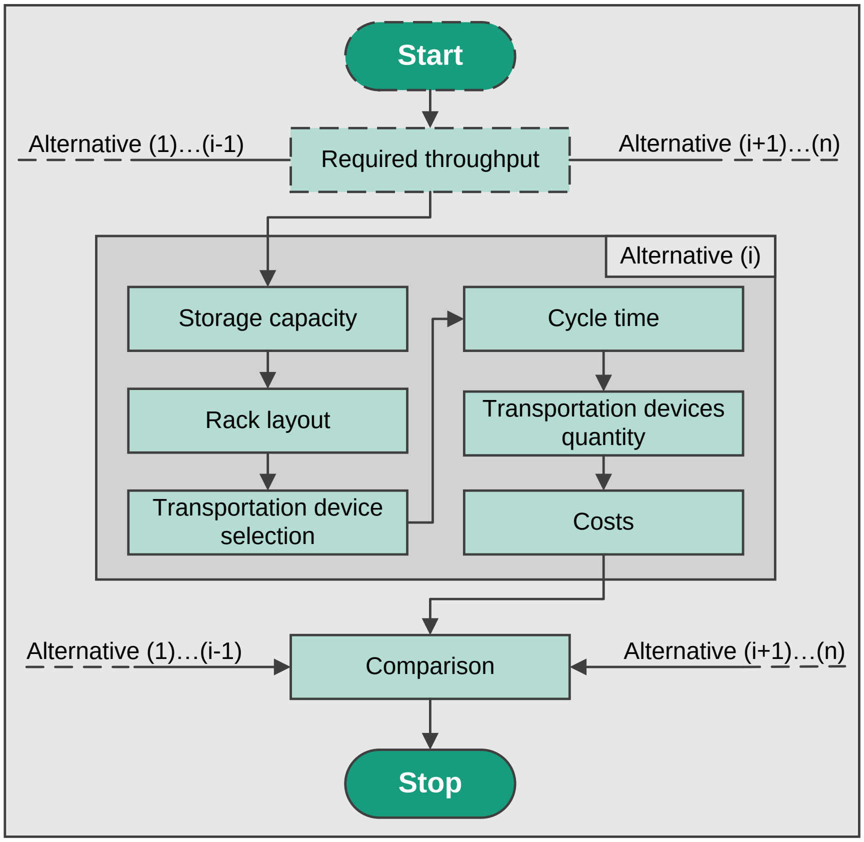

Figure 1: Basic sequence of the heuristics

The heuristics starts with the calculation of the required throughput. This is based on the required number of putting and retrieval operations. Afterwards, the necessary storage capacity is calculated. This is done in a fairly simple way to limit the amount and complexity of data to be collected. Also, the authors believe that in most of the cases the necessary storage capacity is known beforehand. Next, based on space limitations provided by the user a rack layout is determined. Using various guidelines for good storage design (e.g. the length-to-height ratio of racks in an AS/RS) a starting solution is generated. After, the heuristics checks this solution for applicability due to the space limitations and adapts the layout if necessary. The outcome of this step is the length, height and depth of the rack and whole layout block as well as the achieved number of pallet positions and the filling rate. Based on those, a specific type of transportation device is selected out of the pre-selected class. The device has to be capable of working in the proposed layout as well as achieve high driving speeds. To be able to answer the needs of various storage systems a database has to be developed which includes a number of common types for each of the considered transportation device class. Necessary data includes driving and acceleration speed, loading and unloading times and maximum length and height. The data is required for the following step, the calculation of mean cycle time. This is based on the results gained in the previous calculations as well as the share of single and dual-cycle picking in the operation. As the calculation of the cycle time varies strongly between different transportation device classes, a strong focus has to lie on the comparability of the results between the different classes. After the cycle time for a single transportation device is known, the required number of transportation devices is easy to get. One has to take the overall required number of picking operations into account as well as safety factors for availability of technical components and possible upper bounds for transportation devices (a number of 20 forklifts for a storage layout of 150 x 150 feet is likely not applicable). At this stage, a reiteration of the layout is considered, given that the cycle time and/or number of transportation devices is too large. Eventually the costs of the storage alternative are calculated. This includes implementation costs as well as operational costs. Thus, different alternatives can be compared after specified amounts of time (e.g. 3, 5 or 10 years) and the alternative with minimum cost can be selected.

4 Heuristics procedure

The following chapter aims to achieve a more detailed understanding of the developed heuristics. It therefore follows the modular structure which was generally depicted in the previous chapter. It must be noted that for the selection of the specific transportation device out of the pre-selected class no formal procedure is specified. We find that at the current state where no database exists the character of this step is mainly free (e.g. internet research) and therefore not reasonable to specify.

4.1 Required throughput

The calculation of the required throughput of the storage is based on general considerations in [18]. The term throughput is herein defined as the maximum number of putting and receiving operations conducted per time frame. To operate a putting operation the pallets have to be picked up in a certain area and loaded into the desired storage space. A receiving operation starts with the receiving of the pallet from the storage space and ends with its putting in the supply area for further operations [18].

For the planning of storage systems the designer will likely know how much putting and receiving operations per time frame have to be executable by the system. If not, these numbers can be determined from the production or receiving and putting schedules. The calculation assumes that any possible combination of dual cycle operations is undertaken. This is desirable, as a dual cycle combines two single cycles achieving lower driving times and therefore higher performance. Hence, the smaller number of putting and receiving operations is equal to the number of dual cycles which need to be conducted. For the likely case that the quantities of putting and retrieval operations are unequal, a number of operations will remain which cannot be combined to achieve a dual cycle. Therefore, they can only be conducted as single cycles. The total number of operations is the sum of the single cycles plus the number of dual cycles. For further calculations, the share of dual- and single cycle operations is also calculated.

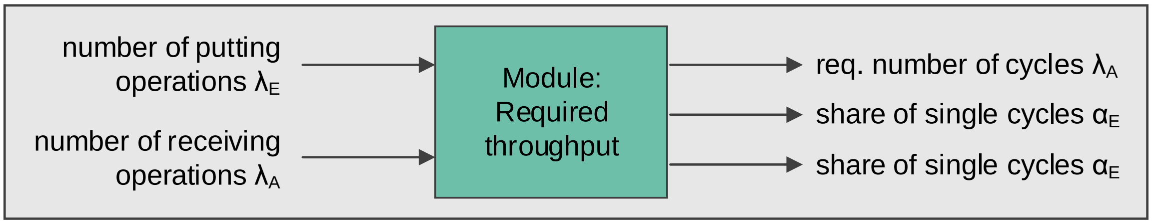

Figure 2: Input and Output of required throughput module

The calculation of the required throughput is necessary for the estimation of the average cycle time and the required number of transportation devices. It takes place at such an early point of time as it is valid for any storage configuration and all the necessary parameters are already available. It is based on the number of putting and receiving operations and serves the required total number of cycles and the shares of single and dual cycles.

4.2 Storage capacity

As well as the previously described module the calculation of the storage capacity is valid for any of the considered technology alternatives. It aims to calculate the number of pallet positions which needs to be included into the system. The goal of capacity planning in general is the calculation of the number of pallet positions which is as small as possible while not leading to scarcity. The existing literature holds a huge amount of approaches for capacity planning. We chose a rather simple approach depicted by [1] for the following reasons. First, at this stage of planning the calculation of storage capacity is likely already conducted. Second, if this is not the case a simple approximation will probably lead to satisfying results for the case of absolutely no knowledge of the capacity so far. Third, [1] describe the approach as commonly used which is why we believe it to be valid. We use it as a basis and expand it slightly to allow for safety stock and consideration of double-deep racks.

The approach we use [1] is based on the standard deviation of the inventory level of the single articles. Generally, the authors assume that for a higher standard deviation a higher inventory level is required to address the growing uncertainty. For a low standard deviation of an article not much inventory is required as the certainty of knowledge about the consumption rate is high. The first step is to analyze the stock level of every article. Under the assumption of standard deviation the stock level of an article fluctuates between $b_{j,max}$ and $b_j = 0$ (Figure 2). The standard deviation s_j is a measure for the degree of fluctuation. The capacity planning is conducted with a certain risk of reaching a stock level of $b_j = 0$ meaning scarcity. This risk is determined by the significance levelα, the probability of running out of stock. A level of $\alpha = 0 \dots 0.05$ leads to immensely large capacities and is not recommended by [1]. The capacity to be planned for every SKU is defined as sufficient if its stock level can fluctuate between 0 and a maximum value consisting of the standard deviation and a certain overhead (determined mainly by the significance level). This way, a certain capacity is calculated for every article.

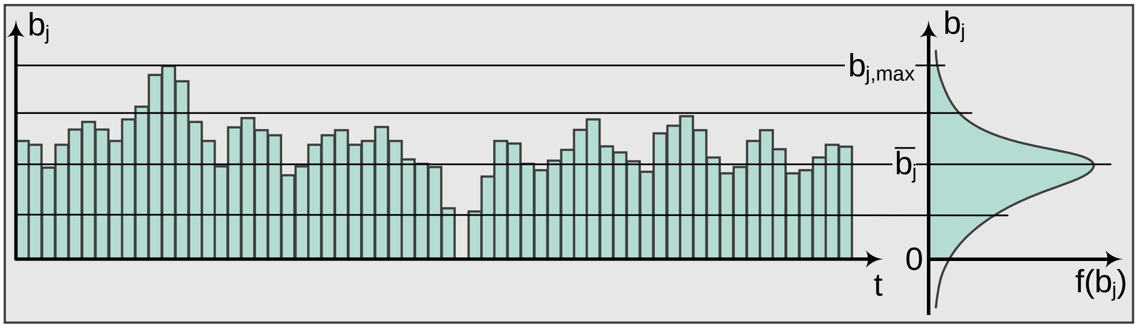

Figure 3: Progress and probability density function for inventory level with standard deviation ([1])

As we only consider shared storage, a compensation of stock levels amongst different articles with statistically independent stock levels needs to be considered to achieve reasonable capacity levels. This leads to a lower capacity than the simple addition of the single capacities for the whole amount of SKUs. Now, the storage capacity for single-deep storage configurations and double-deep mixed article configurations is calculated. For double-deep single article storage the amount of pallet positions needs to be increased as one pallet position is empty but cannot be used if the stock level of one article is an uneven number. We assume that 50% of the articles have an uneven stock level at one point of time. Hence, for every two articles $\frac{n}{2}$ one additional pallet position needs to be added.

The following modules require the calculation of the statistical mean stock level which is also conducted at this point of time. The described calculations require the input of the standard deviation of the stock level of every article. Hence, a good portion of knowledge about the historical data has to exist. The results include the required number of pallet positions which have to be included into the storage layout and the mean stock level.

4.3 Rack layout

In order to create a valid, cheap and efficient layout we follow a basic procedure which is adapted to the characteristics of the various transportation device types. This is described in the following chapter. For further considerations we define a general rack layout for which the parameters are adapted by the heuristics. The general layout contains a number of aisles (an example is depicted in Figure 5). All of them have racks on both of the sides, each of the racks has the same height. For the alternatives with forklift trucks and narrow aisle stackers we leave space for an aisle which allows for movement rectangular to the aisles. For the alternatives with AS/RS it is necessary to provide space for a conveyor system which connects the aisles. Again, we assume a general design for this specific area which is depicted in Figure 4.

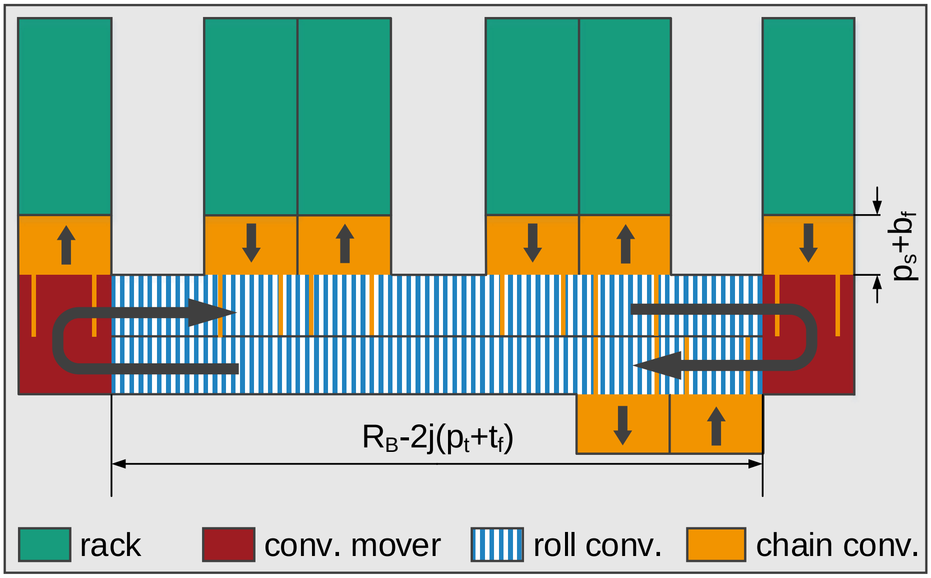

Figure 4: Conveyor system - basic layout

The heuristics firstly creates a layout which aims to minimize travel times. [18] provides an approach which serves the optimum number of aisles based on the theoretical length of a rack which provides space for all of the necessary pallet positions and the rack depth and aisle width. This approach is used to find the starting layout for forklift trucks. For narrow aisle stackers and AS/RS we use another approach. [11] states that an optimum rack has the same length-to-height ratio as the transportation devices ratio for horizontal to vertical velocity. Based on market research we assume a ratio of 4 to 1 for stacker cranes and 6 to 1 for narrow aisle stackers. The designer specifies constraints for the length, height and width dimensions of the storage. In order not to waste any of the available space the racks are as high as the height constraint of the user and the transportation device allow for. This is specified under consideration of e.g. necessary lifting heights or pallet heights.

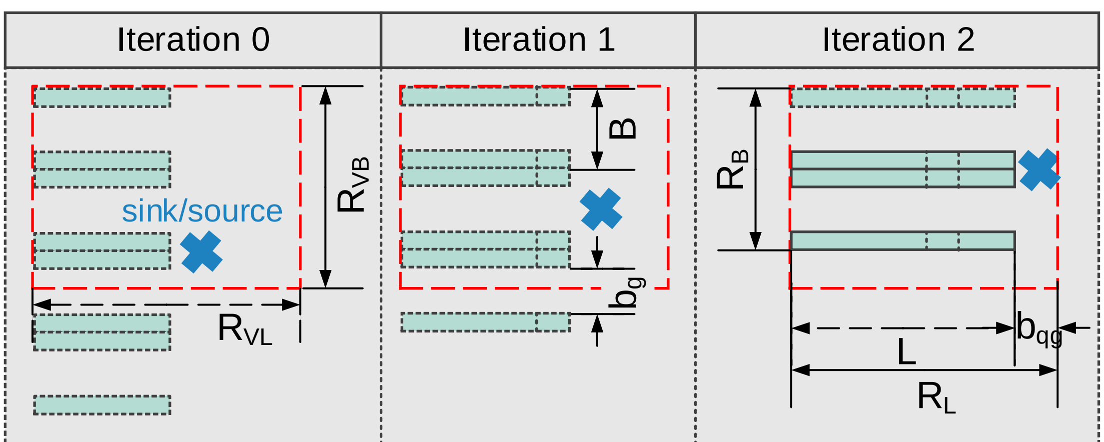

Figure 5: Example of adjustment steps

After the starting solution is created it needs to be checked for adaptability to the current problem. If the starting solution is feasible and within the constraints specified by the designer, it is adopted for the design. If not, the heuristics attempts to adjust the solution to the constraints. For the case of a starting solution which exceeds the width constraint the heuristics decreases the number of aisles and increases their length. For the case of exceeding length the procedure is vice versa. As any designer might recognize the adjustment of the number and length of the aisles might still not lead to a feasible solution. In that case, the heuristics does not include the current alternative to further considerations.

Eventually the achieved number of pallet positions needs to be calculated. It may differ from the minimum number of pallet positions due to some integer conditions for the construction of the racks. For further calculations the filling rate is calculated as well. The alternatives with AS/RS include the described conveyor system which connects the aisles for which the parameters are also determined.

4.4 Cycle time

The calculation of the cycle time is necessary to get a good estimation of the number of transportation devices which is required to achieve the desired performance. At this point of time, we only consider the time which is required for movement within the aisle. We chose this approach as we have no estimation of the required number of transportation devices at this point of time. This is necessary to estimate the probability of a transportation device switching the aisle during a dual cycle. However, as we only consider stacker cranes which serve one aisle the cycle time determined for the alternatives with those is final.

For various technology alternatives we use different approaches. We develop an own, simple approach to estimate the cycle time for forklift trucks. For narrow aisle stackers we use [30] for one-deep storage and [32] for two-deep storage. The cycle time of AS/RS is estimated using the approach of [11]. All of the approaches assume an acceleration and velocity profile as depicted in Figure 6. The module calculates the times required on average for single and dual cycles within one aisle.

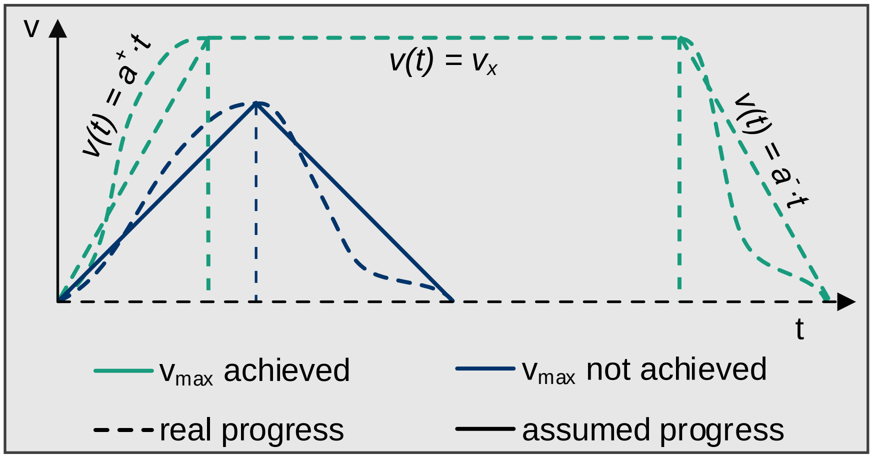

Figure 6: Velocity progress profile

4.5 Transportation devices quantity

In order to achieve the desired performance the number of transportation devices has to be determined. It must be noted that, based on the transportation devices we defined, two different procedures need to be specified. As we only consider stacker cranes which serve one aisle we cannot simply select the number of cranes but have to adjust it along with the number of aisles. In contrast, the quantities for forklift trucks and narrow aisle stackers can be chosen almost freely up to a level at which congestion effects start to show impact.

For forklift trucks and narrow aisle stackers we extend the calculated cycle time with travel times outside of the aisle. Overall, three cycle cases are defined. The first one is a classic single cycle in which the transportation vehicle fulfills one, either putting or retrieval, operation at a time. Generally, a dual cycle operation combines one putting and one retrieval operation. This combination can take place within one aisle or require to change aisles between the putting and retrieval operations. As the number of transportation devices and probability of aisle change strongly correlate they are determined in an iterative manner. The different cases are weighted with the shares of single and dual cycles and the probability of an aisle change. After, they are combined to achieve a single and comparable cycle time.

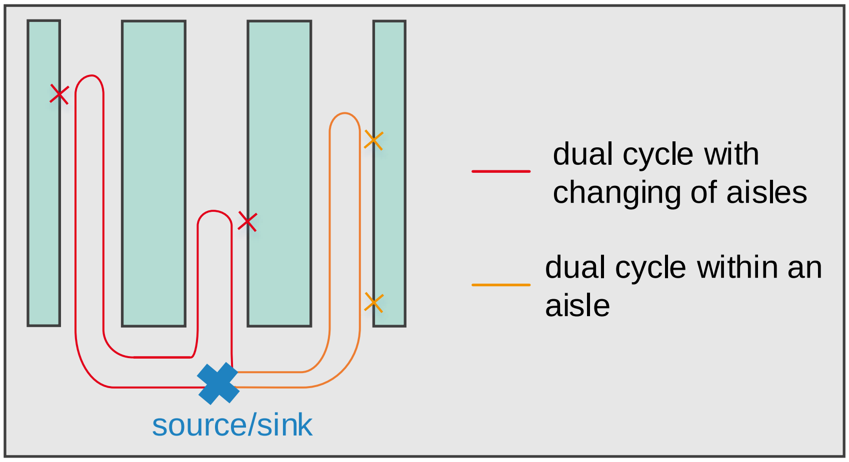

Figure 7: Dual cycle cases

The number of stacker cranes in AS/RS is already determined by the rack layout. The number of aisles is equal to the number of cranes. However, as the number of aisles was initially determined to minimize travel time without any consideration of the desired performance, adaption is necessary. Again, we define three cases. In the first case the performance which is achieved by the configuration is too small. Hence, the heuristics attempts to increase it by increasing the number of aisles within the specified space constraints. If this is not possible the alternative is not further considered. In the second case a performance is reached which is greater or equal to the required one does not exceed it too much (e.g. 120% might still be tolerable). For this case the design is considered as satisfying without the need for alteration. In the third case the achieved performance exceeds the desired performance by far. This leads to a feasible solution which is likely very expensive. Hence, the heuristics tries to reduce performance and costs by reducing the number of aisles and therefore stacker cranes. This is attempted until a satisfying solution is reached or no further adaptation is possible. It must be noted that the performance of the conveyor system which connects the aisles is assumed to be no boundary and hence does not require checking.

4.6 Costs

The costs calculation is the basis for the concluding comparison of alternatives. It is based on the net present value method [Pog11] and includes labor costs, investments for technical equipment and building costs. Certainly, those cost fractions can be extended. Nonetheless, for a basic comparison of technology alternatives we be believe it to be sufficient.

The basic idea of the net present value method is as follows. Any expense made at a certain time is transformed in its value so its worth is represented today. For practical application this means money spent in 5 years can still be used during this time to increase its value. Hence, the expense of the same amount spent in 5 years is cheaper than the expense made today. The different values are summed up to achieve the total net present value of an alternative [26]. In our heuristics, the designer specifies a certain timeframe after which the alternatives are compared. Naturally, the alternative with the lowest costs within this time frame is recommended.

The different technology alternatives include different equipment elements and therefore cost fractions. Commonly, costs for the racks need to be included. Also, every alternative includes some kind of transportation vehicles or devices and space which needs to be paid for. The costs of those may vary strongly (e.g. between a small forklift truck and a stacker crane). As forklift trucks and narrow aisle stackers often have electrical engines, costs for loading stations need to be included as well. Narrow aisle stackers require some sort of guidance system for movement within the aisles. Also, the floor quality needs to fulfill a certain standard and therefore requires refurbishing. Both of those factors induce additional costs. The cost calculation for alternatives with stacker cranes require rail system and steering equipment costs as well as costs for the conveyor system.

5 Example

To verify the practical applicability of the heuristics a case study is conducted which includes two scenarios. The remainder of the chapter firstly describes the initial situation of the case study. After, the gained results are depicted and discussed.

5.1 Initial situation

The heuristics was evaluated using data gained in a project with a German juice producer. The company decided to extend their production capacity and came up with two possible scenarios for both of which the finished goods storage needs to be designed. A new facility has already been acquired. In the first scenario, the facility is used solely as a warehouse. Hence, the already existing building with a width of 260 meters, a length of 65 meters and height of 15 meters is to be used. In the second scenario, the whole production as well as the storage is to be moved to the new facility. This way, the production is put into the existing building and the storage department has to be newly built right next to the production. For that, a space of 75 × 68 meters is available. The local government limits the building height to a maximum of 40 meters.

Only full pallets are put into the storage and delivered to the customers. Hence, only full pallet movements occur. Grocery regulations constitute a minimum time in storage for each of the products of 14 days, this leads to an average stock level of 14,608. The company determines the required number of pallet positions as 17,650. They state that the maximum number of produced pallets per day is 1,371 which leads to 86 putting operations per hour (given 16 hours of operation per day). The maximum number of pallets per day leaving the storage is 867, leading to 55 retrieval operations per hour. This imbalance of input and output maximums results from the lower number of production operational hours than shipping department operational hours. The number of SKUs is as low as 45.

5.2 Results

The results were gained by applying the heuristics to the described situation. If no data was on hand valid assumptions were made. To achieve an understanding of the qualities of the various alternatives the time frame for comparison was chosen from 1 to 10 years. Following the results for the two scenarios are described and afterwards discussed.
For the scenario "warehouse" any of the technology alternatives is applicable. It turns out that the alternatives with stacker cranes are highly expensive and hence not recommended (Figure 8). However, their increase in costs over time is comparably low due to their low labor costs. The alternatives with forklift trucks and narrow aisle stackers show connatural costs. The alternatives with narrow aisle stackers require less space and therefore travel distances, which leads to lower labor costs. Hence, the alternative with two-deep storage and narrow aisle stackers is recommended for time frames of bigger or equal than 3 years. Due to the lower investment costs but higher labor costs the alternatives with forklift trucks is recommended for time frames smaller or equal than 3 years. Intuitively, for this scenario a technology alternative does not have to optimize space dimensions. Also, as the ceiling height of the existing building is low the AS/RS alternatives are not likely to serve cost efficient storages. The heuristics confirms these presumptions quantitatively and therefore reasonably. The recommendation of the heuristics to implement a system with forklift trucks for a time frame of smaller or equal than 3 years is intuitive as well. In contrast, one would probably not have guessed the alternatives with narrow aisle stackers would prove superior in larger time frames. At this point the advantage of a quantitative heuristics becomes evident, as the effort for comparison is low but the gained insight into the problem might be crucial.

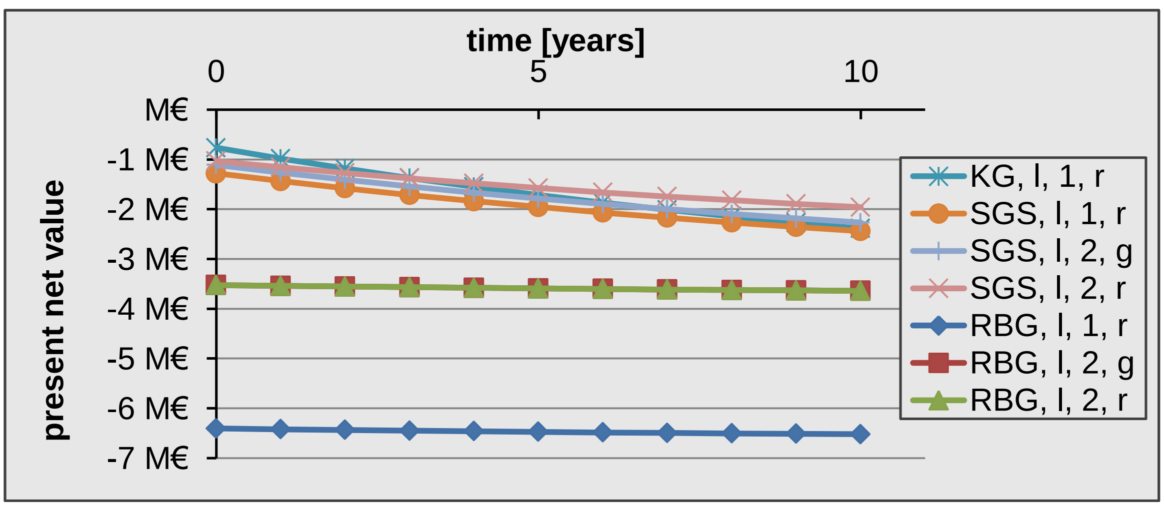

Figure 8: Net present value scenario "warehouse"

As the scenario "production" has strongly limited space, only the AS/RS alternatives with AS/RS turn out to be feasible. However, their performance exceeds the required one with more than 200%. This leads to high costs (Figure 9) but the space constraints allow for no further adjustments. As the performance is not critical, the alternative with one-deep space is eliminated due to its high costs for space and stacker cranes. The decision about single or mixed article storing is indifferent as the number of articles is low so that the additional pallet positions are created either wise. Due to the excess performance the costs of the alternatives created by the heuristics cannot be considered as satisfying. At this point, the disadvantage of the heuristics comes into sight. It is only capable of operating within its created limits. Therefore it cannot react to special requirements such as the minimum storage time of 14 days. An experienced designer could easily come up with another solution such as AS/RS with stacker cranes capable of serving multiple aisles.

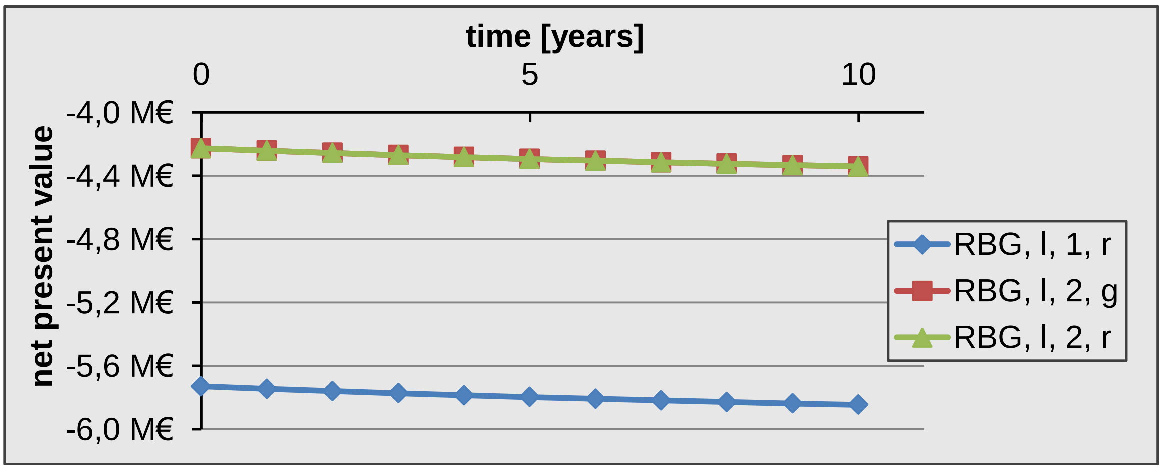

Figure 9: Net present value scenario "production"

6 Conclusions and future work

First of all, we conclude that a huge body of academic literature concerning warehouse design can be identified. This holds for warehouse design workflows as well as specific mathematical models and formulas. Nonetheless, the existing research does not cover the storage planning process completely. Also, it lacks connectivity between the specification of *what* to do (frameworks) and *how* to do it (mathematical models).

Consequently, we develop a heuristics which attempts to bridge the existing gap. The heuristics is a proof-of-concept of a holistic procedure specifying the *how* and *what* to do for the planning of pallet storage systems. For this purpose the heuristics follows a modular structure which leads through the design process on a quantitative foundation. The result of the heuristics is a comparison and assessment of various technology alternatives to be implemented as well as their configurations. Hence, it supports a designer strongly during this process.

Still, the proposed heuristic is a proof-of-concept and requires for development and research. Five main research areas can be identified. First, a selection of calculation approaches should be implemented for each of the specified steps to enhance universality and user-friendliness. Second, the number of technology alternatives needs to be extended to allow for various requirements as was depicted in the example case study.

Third, the implementation of the heuristics in a software tool is crucial for its practical use. Fourth, the quality of the solutions which is achieved by the heuristics needs to be assessed thoroughly. This can be conducted by comparing the alternatives with the ones specialized tools (e.g. [15]) generate. Lastly, the heuristics needs to be integrated into a general design workflow or design concept like the ones of [3] and [25].

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