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Determining the Probability of Unproductive Manipulations in Inland Intermodal Terminal Operations

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ABSTRACT

The paper concerns the method of determining the probability of unproductive manipulations during operations, maintenance or repairs on an inland intermodal terminal. The method is mathematically based on the semi-Markov process. The developed method enables revision of unproductive manipulation frequency and duration. It provides an opportunity to analyse and change inland terminal operations so as to increase productivity.

KEYWORDS

container storage optimisation; inland intermodal terminal; container storage; heuristic procedure; semi-Markov model.

1. INTRODUCTION

The efficiency of inland intermodal terminals is an ongoing challenge. Despite the fact that intermodal transport has been known for decades, various types of scientific papers are constantly making efforts to increase their efficiency. This is related to the general need to improve the efficiency of intermodal supply chains.

Efficiencies are sought at the levels of inland terminal locations, train schedule planning, handling equipment, the logical and physical distribution of containers on the terminal space, timetable design for delivery vehicles taking freight to its destination points. The same links are considered (but much less frequently) in the case of empty unit (container) handling, as if they do not enter the terminal space and do not affect the management of the terminal as a whole.

The issue of inland intermodal terminal efficiency is a complex one. First of all, container terminals cannot be treated as traditional storage spaces. This is due to the fact that at container terminals containers are stacked on top of each other. When unloading containers from trains, it is common for containers to be stacked using several well known methods. The stacking method depends mostly on available terminal space, handling equipment, limited time available for unloading and further on time pressure etc. Regardless of the container sorting and storing strategy, the possibility of unproductive movements should be taken into account.

Unproductive manipulations can be defined as manipulations that generate additional costs and take time [1], e.g. to access a specific container among many others. Unproductive states have a more complex meaning, they include maintenance and repair states as well. Generally, each activity that does not lead to adding value can be taken as unproductive.

Typically, managers do not balance the cost of a longer train stop for unloading/loading and the cost of additional movements of handling equipment at terminals.

Another issue that occurs in the practice of inland intermodal terminals is the illogical setting of the to-do list, causing the operator to spend more time driving around the terminal than on the transhipment activities themselves. This kind of practice restricts the efficiency of the equipment, increases handling costs and can lead to a loss of financial efficiency.

A final element concerning terminal operations that affects the technical efficiency of container terminals is the organisation of maintenance activities, ongoing repairs and preventive maintenance. This is quite often an overlooked issue, which can be of great importance. We underestimate the importance of maintenance activities and their timing, while, especially in complex technical systems, it is enormous.

The aim of this paper is to discuss a model for evaluating the performance of an inland container terminal based on the probability of unproductive and productive manipulations, distinguishing the operational sense of the individual states. Unproductive manipulations will be distinguished as those concern unproductive reallocation and states of unpreparedness understood in the sense of reliability (preventive maintenance and repair). The paper contains a literature study on the efficiency and operations of inland intermodal terminals. The methods used in the inland terminal states and container storing allocation are described. This is followed by a review of the methods used in the determination of the operation process with particular reference to handling equipment maintenance activities.

On the basis of the review, a model will be proposed to assist in giving an assessment of the performance of an inland intermodal terminal. The performance of the model will then be demonstrated using data from a real inland intermodal terminal.

2. LITERATURE REVIEW

The literature review refers primarily to inland road-rail terminals and is related to issues of improving its technical efficiency. We do not refer to the economic issue, as saving unproductive movements leads directly to economic benefits. This reduction is influenced by a well-executed allocation of containers at the terminal, as will be shown in the following text. Unproductive states are also the transition of equipment to states that remove the possibility of using terminal functions. Such states are the state of preventive maintenance and repair. These issues are addressed in the last part of the literature review.

2.1 Determining the efficiency of terminal operations

The challenge of inland intermodal terminal efficiency is addressed in scientific papers for many years. Increasing the efficiency of the supply chain requires constant action to improve the efficiency of the inland terminal itself. The authors in [2] already pointed out the need to parameterise operations by giving examples of efficiency indicators in relation to labour costs.

The authors in [3] propose a simulation model of a container terminal system, which was developed using an object-oriented approach and SIMPLE++ simulation software. The container terminal was assumed to consist of a gate, a container yard and a quay. The equipment used in the container terminal includes loading cranes, gantry cranes, trailers and ramp tractors. Example results are given for the port of Busan. The level of efficiency of the handling systems was studied as a function of the level of filling of the queue of vehicles (ships) waiting to be handled. As the use of cranes increases, the service waiting time increases.

A subsequent paper has presented the possibility of using queuing theory to model terminal operations, e.g. [4, 5]. In a similar way, attempts have been made to address the issues of emerging queues at entry gates [6].

Optimisation experts and researchers have pointed out that the efficiency of container terminals comes down to agile management of operations in the storage space (yard planning). The authors in [7] noted that task congestion is one of the most important causes limiting port efficiency, such as port throughput. Congestion can refer to situations where too many modes of transport are waiting to be loaded, too many cargoes are handled in a small area, or traffic within the yard is unregulated. These rather practical considerations were met with the recommendation to increase the level of automation. Unfortunately, as is well known, this comes at a huge cost that only the biggest players in the world can afford. For land terminals, automation remains at the level of very distant plans.

In later years, attention began to be paid to the environmental aspects of terminal operations. In paper [8], an approach was established in which the aim is to reduce unproductive operations concerning their environmental impact. This is treated explicitly as waste reduction and management (waste management). The importance of 'green operations' was cited by many authors [9, 10]. Special attention has been paid no longer to mere management in the storage space, but to 'sustainable' operations. The research carried out showed that accountability for 'green practices' depends on well-chosen procedures and is the result of a strong commitment by managers.

The paper cited above refers primarily to maritime terminals, where operational efficiency appears to be extremely important. However, inland terminals, due to the lower volumes handled, need efficiency even more. This need does not arise from congestion, but from the need to reduce unnecessary movements. Thus, the aim is to increase the environmental and economic efficiency of such points.

Research [11] contains a method that has made it possible to determine the type of transport and management at a small container terminal, the organisation of the last mile distribution, the testing of the time of operations through simulation and the comparison of the physical changes at the terminal with the determination of the costs of concepts and upgrades. Time and cost constraints were optimised, with the result that the economic calculations made are highly relevant to the start-up of any intermodal system, and the initial investment is recovered. The overarching idea of this paper is to propose coupons to give flexibility to rail services. In this way, terminals can be smaller, and the equipment volume can be significantly reduced for the same level of service. Road transport was treated as a complementary service to rail services, with the ultimate aim of reducing traffic. The possibility of reducing pollution caused by road traffic was highlighted in this paper.

Simulation methods directed at improving efficiency were also presented in the paper [1]. In this case, it was noted that container allocation was a key factor affecting the efficiency of terminal operations. The proposed model determines a feasible sequence of loading operations that minimises the costs associated with container storage. The model was validated using data from one of the observed inland terminals, and the model was able to significantly reduce unproductive handling, which, in the case of the inland terminal where the simulation was carried out, took away around 60% of productivity. The method saved almost 18% of unproductive movements.

An allocation method combined with the use of the sequence of operations performed has been proposed in publication [12]. In this case, authors are dealing with a heuristic method that consists in assigning values to the individual load units, determining the routes of the vehicles at the terminal and, on this basis, determining the sequence of orders to reduce the number of movements and reduce the time taken to perform train unloading operations. This approach assumes that train handling is the resultant of the times of all individual operations, hence each operation has an impact on the final result achieved.

Another direction is to increase automation as a guarantor for improving the efficiency of operations. The paper [13] refers to the possibility of increasing automation in small ports and inland terminals. The paper [14] discusses the technical merits of introducing various types of upgrades that increase the level of automation. Both papers omit issues of economic efficiency, focusing solely on technical issues. The paper [15] provides a model for the development of inland depots of empty containers with increasing trade volumes and trade imbalances. The results indicate that inland terminals can reduce the number of empty kilometres travelled and the associated costs and improve the efficiency of the logistics system. It was noted that the location of terminals is of particular importance for the environment or region.

An example of this approach can be seen in the paper [16], which defines containerised cargo flows between the port of Rijeka and its inland destinations by road and rail. Based on the analysis of container cargo flows, a potential location for the construction of an inland terminal is identified in terms of shifting container flows from road to rail. Further, the paper shows that the position of an inland terminal in the transport network depends on several elements, the selection of which has a significant impact on its final location. The article presents a quantitative method for determining the optimal location of an inland terminal at a node of the rail network, primarily based on transport cost savings. A key condition of the model is that all containers that are currently transported by road are to be transported primarily by rail from the seaport to the proposed inland terminal location. The application of the model on a real network has proven its usefulness, especially when additional criteria are needed in the decision-making process of determining the location of an inland terminal.

The efficiency of container terminals is therefore dealt with in various ways and it is difficult to establish one precise definition of it. These are issues related to the fulfilment of individual indicators, which nowadays increasingly refer to the issue of ecology and CO_2. They refer to individual terminal operations, as well as known attempts to approach the organisation of terminal operations comprehensively. Some authors link the efficiency of terminal operations to a suitable location, which is related to traffic and, for example, queuing of truck entries and exits and traffic within the region served.

In the following section, a greater focus will be directed towards the issues of assigning work to machines and allocating loads within the terminal, as fundamental determinants of effective task management.

2.2 Using terminal space allocation to increase container terminal efficiency

As shown in the paper [1], even in a maritime terminal about 60% of manipulations can be unproductive. The example shown states an approximate 50% occupancy of the storage areas. The main reason for such a high percentage of unproductivity is the lack of information about the scheduled release of containers to the consignee. Therefore, whenever possible, the level of planning of container distribution at the terminal should be increased to reduce the number of unproductive manipulations.

Optimisation of container distribution at the terminal is a nondeterministic polynomial time (NP hard) issue, and there is no single way to improve terminal efficiency in this respect. Authors often resort to different types of heuristic methods and solutions supported by simulation models. Practical storage space allocation strategies refer to individual containers or groups of containers. Space allocation involves assigning containers to storage blocks and assigning them specific positions within the selected block. The second strategy relates to assigning groups of containers to storage locations.

This type of approach was presented in the paper [17], where a generic algorithm was used for optimisation, and the aim was to reduce the cost of unproductive movements. The calculations were carried out for two rows in the landfill, which is an assumption that deviates from practice.

Paper [18] focused on increasing the efficiency of slot use, defining its efficiency through occupancy time.

An interesting approach was presented in the paper [19], where the container allocation problem concerned an inland waterway. The paper presented a two-stage simulation that allowed a small-scale minimisation of the number of manipulations. The first simulation was a micro-scale, while the second was a full-scale experiment confirming the validity of the mathematical assumptions presented.

A study [20] analysed the impact of handling equipment on the efficiency of work execution. The different types of handling equipment that can be used to operate a container terminal were discussed and their impact on the terminal layout was described (reachstackers, gantry crane, rubber tyred gantry crane). Different categories of container terminal layout were defined.

The question of the shape of storage space was also addressed in the paper [21]. It pointed out that there is a difference between durations of individual sequences of operations (container retrieval time, registration time at the gateway), which is an excellent assumption for the allocation of container spaces. In a way, this is a reversal of the situation where the number of execution points of successive operations can be multiplied rather than stacking heuristics to an existing machine resource.

In the paper [22], attention is paid primarily to reducing fuel consumption, which can be explained as an attempt to reduce the cost of handling cargo units.

With regard to maritime terminals, heuristics have been presented that approach the allocation issue somewhat differently [23]. In this paper, the authors presented a stochastic model. In the first stage, a decision is made to allocate sub-blocks for incoming containers. Once this decision is made, it remains unchanged for the entire period. The second stage is to solve the allocation of a container and a handling equipment to a specific loading unit.

More recently, thanks to the development of simulation methods, more and more work has been done on dynamic models and automatic terminals. The publication [24] addresses both of these problems. It is pointed out that research on traditional terminals is well developed, but research on automated terminals, and especially on storage space management, is at an early stage. The method presented assumes similar steps to the previous article. In the first step, a model is created to balance the workload of the handling equipment including the distance to move containers to the transhipment site, and the second step involves assigning work to specific handling machines.

Considering the presented publications, it is reasonable to believe that this line of heuristics will continue. Similarly, the development of terminal automation and the popularisation of Industry 4.0 solutions is a direction that is likely to be worked on in the coming years.

The heuristics presented are nowadays most often supported by simulations. They themselves are two stage models, less often three or multiple stage models, as in the case of [12].

2.3 Assigning operations to handling equipment at container terminals

As demonstrated in the previous section, heuristics for container yard management typically consist of at least two parts: space allocation for the container and task allocation to the handling equipment. In the following section, approaches that lead to optimised handling equipment allocation will be presented.

Note that inland terminals usually have several pieces of handling equipment in operation, and in addition they may be of different types, such as a reachstacker and gantry crane. In terminals where the storage blocks are regular it is worth considering the use of overhead cranes, in less regular spaces the reachstacker may be the only solution. Collaboration between two pieces of handling equipment can also be explored. Such cooperation often has to take place when the rail track and/or truck area is not served by an overhead crane. However, then practically any manipulation of the crane could be considered unproductive, as it is not directly related to the loading/unloading of the means of transport. However, this is intentional: the loading fronts are handled by other handling equipment, e.g. reachstackers and the storage blocks are handled by the overhead crane (which, when electric, works much more cheaply). In this article we deal with the situation where unproductive manipulation is considered as a container movement from one location to another because of the need to retrieve the container underneath.

In literature this problem is known as the “location assignment (stacking) problem” as it describes the allocation of containers to stacks [7].

The problem to be analysed falls within the area of planning and scheduling of service tasks. In this area, we can speak of so-called short, medium and long term planning [25, 26]. At the same time, from the point of view of the operation of container terminals, the greatest challenge is related to the so-called short-term planning, which includes the scheduling of daily tasks. This is a job-shop class problem, which concerns two aspects: determining the execution time of individual tasks and recognising the potential of the necessary resources.

There are three typical decision objectives in scheduling:

a) lead time, which measures the time required to complete a task;
b) punctuality, which measures the coincidence of a correctly completed task with the deadline set;
c) productivity, which measures the amount of work completed in a set period of time.

The selection of an appropriate target as well as an optimal model, adapted to the conditions of the system under study, is a complex issue. Three basic approaches to job-shop scheduling based on search algorithms are used:

1) exact (linear or non-linear programming, among others),
2) approximate (e.g. worst-case analysis),
3) heuristic (e.g. genetic algorithms, ant algorithms, particle swarm optimisation (PSO) algorithms).

Exact and approximate algorithms can be used only for a selected class of problems. Their main disadvantage is the level of model complexity and strong constraints, which often prevent an optimal solution from being obtained [27].

The paper [28] compares the job shop and flow shop problem using the example of automatic handling equipment. Attention was drawn to the very small number of publications using both approaches.

However, unnamed algorithms are used in this way, if only in heuristic approaches and simulation modelling. The article [29] points to the following methods: expert systems, simulation methods, neural networks, taboo search algorithm, ant algorithms, particle swarm optimisation, immune algorithm, multi-agent method, fuzzy logic, and also hybrid methods, using several of the available methods.

Scheduling issues are linked to maintenance issues and disruption in general. An increasing number of publications consider the issues of non-linear operation and the possibility of adverse events, as in the paper [30]. With the rapid expansion of the global container trade, quay cranes and other resources at container terminals are suffering from increasing workloads. To reduce the likelihood of failure, quay cranes usually require preventive maintenance. In the cited article, as in previous ones, heuristics are presented that solve the problem of maintenance and scheduling of equipment.

The paper [31] presents a model based on determining the risk associated with the preventive-predictive maintenance process of gantry cranes in a container terminal. The task of the model is to coordinate the maintenance process in order to minimise the risk of inefficiency of the gantry cranes. A sequential Markov chain

Monte Carlo simulation model was used for this. It was also assumed that the presented problem belongs to non-linear stochastic optimisation problems and is efficiently solved using particle swarm optimisation (PSO) algorithms.

In the work of [32], digital twin technology is used to establish a virtual but realistic repository and organise the work inside it. Disturbances representing maintenance activities and equipment failures were introduced into typical scenarios. In this way, simulations were carried out for the storage area, automated cranes and automated guided vehicles (AGV). Three key technologies were adopted for the scheduling itself: the Internet of Things (IoT), virtual reality and digital threading.

In the paper [33], we find an analytical approach to estimating the reliability of a transhipment system using a deterministic approach based on a Markov model. Similarly, Markov modelling issues for train scheduling are referenced in [34] and [35]. There has also been a discussion on the use of slightly more flexible damage functions for transhipment systems [36].

Paper [37] revisited the issue of indicators and highlighted the need to provide reliable solutions that take into account maintenance issues.

2.4 Literature review summary

The presented literature review is related to the issues of operations management at container terminals. They include the topics of allocating container storage locations, scheduling the handling equipment and planning equipment availability. Altogether, these are issues that can be solved by various types of hybrid solutions, often using a combination of analytical and simulation methods. However, the paper does not combine the issues of unproductive manipulations in equipment maintenance operations, but rather builds models that treat these issues separately. Meanwhile, both types of unproductive activity must be taken into account for full planning or efficiency evaluation, as both generate costs and introduce disruptions. They can also give rise to cascading disruptions. In the following section, a model for assessing the efficiency of an inland container terminal based on a semi-Markov model is presented. This model allows the use of arbitrary probability distribution functions of container manipulations and transitions between them. Furthermore, the model does not address the management of the terminal space itself or the assignment of tasks to handling equipment. Instead, it addresses the issue of the occurrence of unproductive manipulations, but not taking into account maintenance or repairs problems.

3. HANDLING OPERATIONS MODEL

In the following section, a model will be presented that can be used to assess the performance of the handling equipment at the inland container terminal.

The model does not apply to a single operation of any machine involved into the process of container handling. Instead, it will work well for evaluating the inland terminal as a system. The mathematical modelling is based on a semi-Markov process, which, using historical data, will allow us to determine the probability of occurrence of conditions that we consider undesirable.

The following section will present:
- a state graph of terminal processes and their linguistic description,
- a mathematical model of processes in semi-Markov notation,
- a computational model to enable practical application of the presented model.

3.1 Model description

Container transhipment involves the movement of containers at inland terminals. This is carried out by appropriate handling equipment, e.g. gantry cranes, reachstackers, forklift trucks etc. A graph of states is shown in *Figure 1*. The differentiation of manipulations makes it possible to determine:
- the operating time of the handling equipment during loading,
- the operating time of the handling equipment during yard work,
- intensity of damage during handling,
- intensity of damage when other work schedules are carried out.

The transhipment phase plays an important role in the implementation of intermodal transport. During the road and rail phases, there is a transhipment state in which the road and rail vehicles are not operating. It is during this time that the transhipment equipment is in operation.

During the handling phase, handling equipment is in the following states:

State 1 – standstill, includes: organisational standstill, standstill pending a handling request.
State 2 – transhipment (to rail/car), includes: unloading rail wagons or road vehicles, loading rail wagons or road vehicles.
State 3 – handling labour, includes: labour involving the relocation of integrated containers, preparation of containers for loading onto rail/road.
State 4 – preventive maintenance, includes: technological preparation, service stop, technical service.
State 5 – repair, includes: unscheduled maintenance after damage to the equipment to restore it to a serviceable condition.

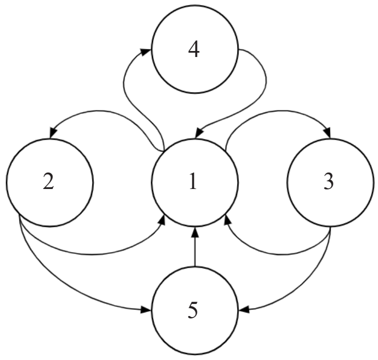

Figure 1 – Graph of operational states in the transhipment process

The initial state of the transhipment phase is a standstill – state 1. This is also the state of waiting for a transhipment request or the execution of yard work. Once the need for transhipment is reported, the handling equipment switches to this state (state 3). If there is a need to carry out operations to translocate the container units within the yard, without the need for reloading, then the transhipment equipment will be in state 2. Successful completion of the work associated with states 2 and 3 brings the equipment back to state 1, again waiting for new tasks. In the course of carrying out the activities resulting from being in states 2 and 3, a device may break down. It then moves to state 5, where it is repaired. The handling equipment can reach the state of preventive maintenance (state 4), however, it is only possible from state 1. After both breakdown or preventive maintenance, the handling equipment reaches state 1 – standstill, awaiting an operation request.

3.2 Mathematical model

Semi-Markov processes are stochastic processes. The definitions are presented in the papers [38], [39] and [40].

According to these, there are the following ways of defining semi-Markov processes:

- using the pair ($\boldsymbol{p}$, $\mathbf{Q}(t)$), where $\boldsymbol{p}$ is the initial distribution of the process, $\mathbf{Q}(t)$ is the matrix of distributions of transition times from state i to j;
- using the triple ($\boldsymbol{p}$, $\mathbf{P}$, $\mathbf{F}(t)$), where $\boldsymbol{p}$ is the initial distribution of the process, $\mathbf{P}$ is the transition probability matrix, $\mathbf{F}(t)$ is the matrix of the distributions of the duration of state i when state j is next;
- using the triple ($\boldsymbol{p}$, $\boldsymbol{e}(t)$, $\mathbf{G}(t)$), where $\boldsymbol{p}$ is the initial distribution of the process, $\boldsymbol{e}(t)$ is the matrix of transient probabilities of the process from state i to j, when in state i the process stays for time x, $\mathbf{G}(t)$ is the matrix of distributions of state durations.

The study assumes that the process will be defined by a pair ($\boldsymbol{p}$, $\mathbf{Q}(t)$). In productivity states, the transhipment phase system elements are contained within the set $S(0,1)$ that consists the elements: 0 for non-productive, and 1 for productive activities.

The operational states are included in the set $T(1,2,3,4,5)$ and are similar to the states presented in *Figure 1*. These are intentional states whose random variables are all independent and denote: 1 – standstill (waiting for work), 2 – handling, 3 – yard work, 4 – preventive services, 5 – repair.

The operational relationships shown in *Figure 1* can be overlaid with productivity relationships. This will result in a Cartesian product $S \times T$ that forms pairs: {(0,1), (1,1), (0,2), (1,2), (0,3), (1,3), (0,4), (1,4), (0,5), (1,5)}.

Now, let us assume that the model allows for the existence of the following pairs in the transhipment phase: S_1 (1,1), S_2 (1,2), S_3 (0,3), S_4 (0,4), S_5 (0,5).

3.3 Kernel of the transhipment phase

Let us assume that the action system under consideration can be described by a semi-martingale process $\{X(t){:}t \geq 0\}$ with a finite set of states of the process $S_p = \{1, 2, 3, 4, 5\}$. In this case, the kernel of the process will be defined by the matrix:

$$\mathbf{Q}^p(t) = \begin{bmatrix} 0 & Q_{12}(t) & Q_{13}(t) & Q_{14}(t) & 0 \\ Q_{21}(t) & 0 & 0 & 0 & Q_{25}(t) \\ Q_{31}(t) & 0 & 0 & 0 & Q_{35}(t) \\ Q_{41}(t) & 0 & 0 & 0 & 0 \\ Q_{51}(t) & 0 & 0 & 0 & 0 \end{bmatrix} \tag{1}$$

where:

$p_{ij} = \lim_{t \to \infty} Q_{ij}(t)$

$\dfrac{Q_{ij}(t)}{p_{ij}} = F_{ij}(t)$, where $F_{ij}(t)$ is the probability density function of the random variable T_{ij} denoting the duration of state i, when the next state will be state j.

Let the vector $\boldsymbol{p} = [p_1, p_2, p_3, p_4, p_5]$ be the initial distribution of the process, which takes the following form:

$$\boldsymbol{p} = [1, 0, 0, 0, 0]. \tag{2}$$

The transition probability matrix is then given with:

$$\mathbf{P}^p = \begin{bmatrix} 0 & p_{12} & p_{13} & p_{14} & 0 \\ p_{21} & 0 & 0 & 0 & p_{25} \\ p_{31} & 0 & 0 & 0 & p_{35} \\ p_{41} & 0 & 0 & 0 & 0 \\ p_{51} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

3.4 State boundary probability and boundary readiness

The probability distribution of a semi-Markov process can be calculated based on the stationary distribution of the inserted Markov chain and the expected values of the duration of the process states.

The transition probability matrix of an inserted Markov chain with a set of states {1, 2, 3, 4, 5} is written in *Equation 3*.

According to [38], [39] and [40], the system of equations for the stationary probabilities $\pi_1, \pi_2, ..., \pi_5$ of an inserted Markov chain takes the form:

$$\begin{cases} \pi_1 = p_{21}\pi_2 + p_{31}\pi_3 + p_{41}\pi_4 + p_{51}\pi_5 \\ \pi_2 = p_{12}\pi_1 \\ \pi_3 = p_{13}\pi_1 \\ \pi_4 = p_{14}\pi_1 \\ \pi_5 = p_{25}\pi_2 + p_{35}\pi_3 \\ 1 = \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 \end{cases} \tag{4}$$

The expected values of state durations are of the form: $E(T_1)=\int_0^\infty td\left[F_{12}(t)+F_{13}(t)+F_{15}(t)\right]$,

$E(T_2)=\int_0^\infty td\left[F_{21}(t)+F_{25}(t)\right]$, $E(T_3)=\int_0^\infty td\left[F_{31}(t)+F_{35}(t)\right]$, $E(T_4)=\int_0^\infty td\left[F_{41}(t)\right]$, $E(T_5)=\int_0^\infty td\left[F_{51}(t)\right]$.

The limit distributions of this semi-Markov process bears the form:

$$P_1=\frac{\pi_1 E(T_1)}{\pi_1 E(T_1)+\pi_2 E(T_2)+\pi_3 E(T_3)+\pi_4 E(T_4)+\pi_5 E(T_5)} \tag{5}$$

$$P_2=\frac{\pi_2 E(T_{p_2})}{\pi_1 E(T_1)+\pi_2 E(T_2)+\pi_3 E(T_3)+\pi_4 E(T_4)+\pi_5 E(T_5)} \tag{6}$$

$$P_3=\frac{\pi_3 E(T_{p_3})}{\pi_1 E(T_1)+\pi_2 E(T_2)+\pi_3 E(T_3)+\pi_4 E(T_4)+\pi_5 E(T_5)} \tag{7}$$

$$P_4=\frac{\pi_4 E(T_{p_4})}{\pi_1 E(T_1)+\pi_2 E(T_2)+\pi_3 E(T_3)+\pi_4 E(T_4)+\pi_5 E(T_5)} \tag{8}$$

$$P_5=\frac{\pi_5 E(T_{p_5})}{\pi_1 E(T_1)+\pi_2 E(T_2)+\pi_3 E(T_3)+\pi_4 E(T_4)+\pi_5 E(T_5)} \tag{9}$$

The probability of productive states takes the following form:

$$K_p=P_1+P_2=\frac{\pi_1 E(T_1)+\pi_2 E(T_2)}{\pi_1 E(T_1)+\pi_2 E(T_2)+\pi_3 E(T_3)+\pi_4 E(T_4)+\pi_5 E(T_5)} \tag{10}$$

3.5 The calculation procedure

The next step will be the presentation of the model using a simulation for the calculations, as shown in *Figure 2*.

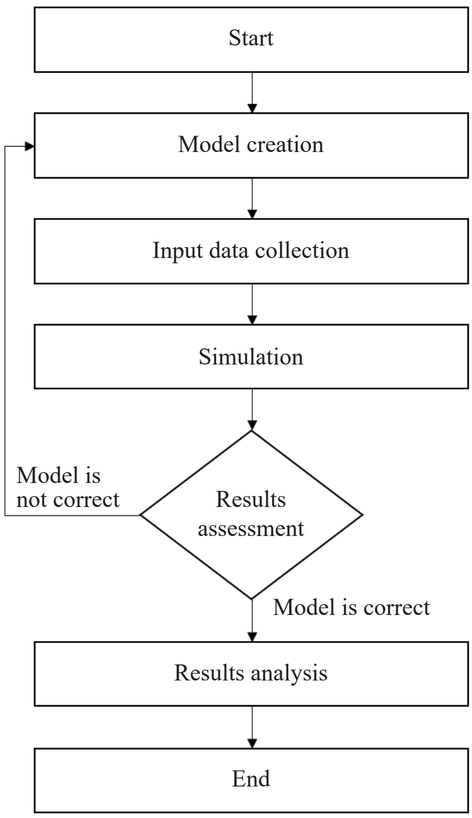

Figure 2 – A model for conducting the analysis

First, a preliminary model structure should be provided. The model structure shown above consists of five operational and two productivity states defined by sets *T* and *S*, which can be taken as a starting point for possible modifications. If necessary, it is possible to add states defining activities that are important from the point of view of the person conducting the analysis. Thus, it is possible to focus on productive or unproductive manipulations performed separately in empty and full containers, to divide container sizes (e.g. traditional 20'; and 40'). However, the mathematical description should then be adapted to a different model structure.

The next step is the collection of input data. This is simply the acquisition of data determining the probability distributions of transitions between manipulations. Data preparation is described in more detail, for example, in the paper [41].

The following step is to carry out simulation calculations and evaluate the results on this basis. If a result is not satisfactory, then the source of the problem should be sought either in the structure of the model or in the adequacy of the prepared input data for the calculations. If, in the course of this verification, the evaluation of the results is correct, then one can proceed to the results analysis stage. In this part, we evaluate the values obtained, which are the stationary probabilities of the occurrence of process states. The numerical results will allow us to determine which of the states consume the most time, and the analysis, supported by the forms of probability distributions of transitions between the manipulations, will allow us to determine which of the states/transitions lead to the greatest waste. The exact limits of acceptable and unacceptable states will depend on the individual characteristics of the terminal. The paper proposes an illustrative view of this issue by presenting it in *Figure 3*.

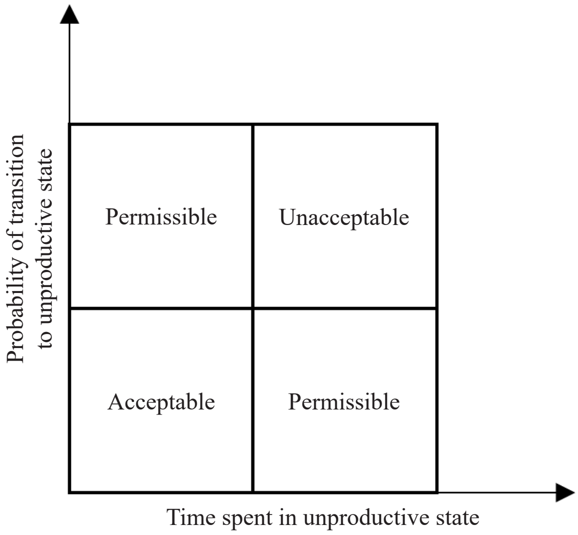

Figure 3 – Simplified view of the interpretation of the results

This is a simplified scheme for interpreting the results, which distinguishes between states of system operation: correct, permissible, unacceptable.

The first occurs when the probability of transition to an undesirable state is low, as is the length of time in such a state. Action should focus on controlling it and continuing to maintain it.

Acceptable states are when:

- the probability of transition to an undesirable state is high, but the duration of state is small, or
- the probability of transition to an undesirable state is low, but the residence time is high.

Both cases require an analysis of the causes of the situation. A small residence time in the undesirable state is in itself beneficial, but frequent transitions to it can cause disruptions in the continuity of handling orders. In the second case, infrequent transitions to an unfit state are beneficial, but if the state is prolonged, equipment does not perform productive work.

The most difficult area is where the probability of moving to an undesirable state is high and the residence time in these states is also high. It is then necessary to strongly revise the activities undertaken in the terminal in order to pursue more favourable states.

4. MODEL IMPLEMENTATION

In the following section, system operation is presented using the example of an inland intermodal container terminal. Based on the research carried out, parameters were estimated to determine the readiness of the intermodal transport system. The study was carried out by means of an expert survey supported by a questionnaire, and employees of the aforementioned transhipment point were appointed as experts.

The data collection was conducted in 2012 on one of the inland terminals in Poland. Despite the fact that the data come from several years ago, it does not change their usefulness for further analyses. The observations were carried out in series of several days for 6 months. Data was collected on the presence of machines in various operating and reliability states. The aim of the study was to determine the frequency of occurrence of individual states, i.e. to determine with greater care the reasons for achieving a given value of the availability factor, rather than some other. Previously, this indicator was not calculated for this terminal.

The starting point for the analysis and calculations is the state graph shown in *Figure 1*, and the mathematical description is included in *Equations 5–9*. Data on both use and operation are needed to determine the parameters of the model. The aggregated results of the observations are presented in *Tables 1–3*. The data come from several months of observations. An attempt to interpret the data for subsequent months separately is unjustified. On the one hand, the probabilities of transitions in subsequent periods will change, which can be interesting, but there are reasons why this cannot be done. There are several issues to note:

1) In the following months there was a different number of operations *(Table 1)*, i.e. the frequency of transition to the operation state was different (which is discussed later),
2) The intensity of the transition to the “maintenance” state is different, because the average fuel consumption is different depending on the number of operations (*Table 2*), and thus the refuelling intensity per unit of time changes.
3) According to the data in *Table 3*, not every month a failure was recorded, therefore in some months the probability of going to the repair state would be “0”. For this reason, and in accordance with the recommendations of the authors that used Markov modelling, it is worth collecting data from a longer period. Unfortunately, we only have data available for a few months in this analysis.

These reasons make it a great simplification to calculate data for one month and extend these data to subsequent periods.

Returning to the observations made, the research consisted in the observation of everyday activities that were catalogued by assigning activities to a specific state. Additionally, the obtained data was refilled with information from the terminal management system. *Table 1* shows information on the mileage of the handling equipment, the number of ‘moves’ and the fuel added.

A preliminary analysis determined the fuel consumption of the container truck by month. In those months where the number of equipment movements is lower, the average fuel consumption per kilometre is lower, but the consumption calculated per operation increases. An increase in the number of transhipments results in a decrease in consumption per container operation. *Figure 4* shows the dependence of fuel consumption on the number of manipulations per month, with the trend line marked (2nd degree polynomial approximation). Ideal-

Table 1 – Information on the operating parameters of the handling machine

Month	End of month odometer [km]	Refuelling per month [l]	Number of container wagon movements
February	15146.6	800	680
March	15249.5	800	544
April	15304	700	408
May	15385.3	700	625
June	15476	800	696
July	15521.6	800	366
August	15610	700	591
September	15685	700	599

ly, direct transhipment from rail wagon to a lorry trailer or vice versa is organised without transhipment of the container to the yard, i.e. the creation of additional traffic for the transhipment wagon.

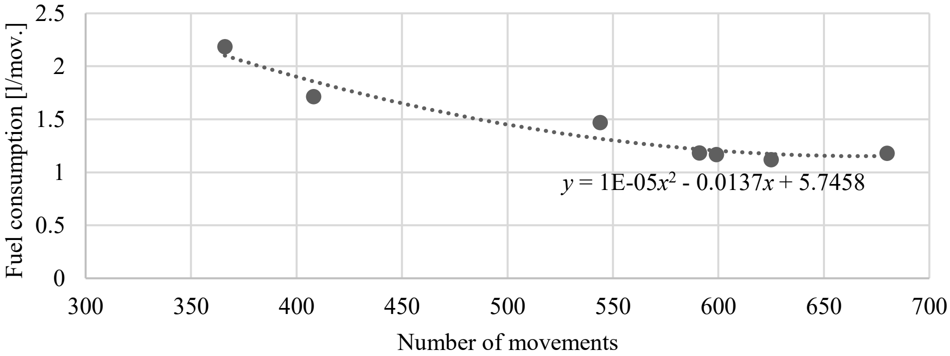

Figure 4 – Fuel consumption as a function of the number of manipulations per month

One reachstacker movement took an average of six minutes. The operating time data for the following observed months are shown in *Table 2*.

Table 2 – Number of handling equipment manipulations in months

Month	Type of transhipment			Number of movements	Operating time [min]
	d-p	k-p	p-k		
February	80	390	210	680	4080
March	103	225	216	544	3264
April	94	156	158	408	2448
May	115	258	252	625	3750
June	117	338	241	696	4176
July	98	133	135	366	2196
August	129	199	263	591	3546
September	115	222	262	599	3594

d-p – road-yard transhipment, k-p – rail-yard transhipment, p-k – yard-rail transhipment

The number of manipulations, hence the working time, varies from month to month. The difference between the month with the smallest number of manipulations and the one with the largest is almost double. Due to the lack of data to determine the distributants of operating time, it was assumed that all activities are determined by an exponential distribution and that the value of the distribution is constant in successive months.

During the study period, five defects occurred on the loading vehicle. The number of repairs, checks and inspections is shown in *Table 3*. Based on the information gathered, the input parameters for the state probability calculations were prepared and are presented in *Table 4*.

Analysing the data from *Table 2*, we obtained the values for calculation in *Table 4*. P_{ij} values are given from probability density functions. The detailed method is presented in the papers [40] and [42]. It explains in detail the interpretation of basic information as input data to the computational model.

The graph showing the probability of occurrence of the states is shown in *Figure 5*. The state with the highest probability of occurrence is the standstill state, for which P_1=0.383. The next state is the transhipment state, and its probability of occurrence is P_2=0.326. In principle, only these two states are productive, and the probability of their occurrence is 0.709. A characteristic of the inland terminal under study is that the equipment is most often in the standby state.

Table 3 – Number of repairs by months

Month	Overview	Repair
February	1	1
March	0	0
April	0	0
May	0	0
June	0	1
July	1	1
August	0	1
September	0	0

Table 4 – Values of input parameters for calculations

$E(T_1)$	3.613	p_{12}	0.161	p_{31}	0.999
$E(T_2)$	2.254	p_{13}	0.803	p_{35}	9E-04
$E(T_3)$	0.676	p_{14}	0.036	p_{41}	1
$E(T_4)$	0.5	p_{21}	0.999	p_{51}	1
$E(T_5)$	0.957	p_{25}	9E-04		

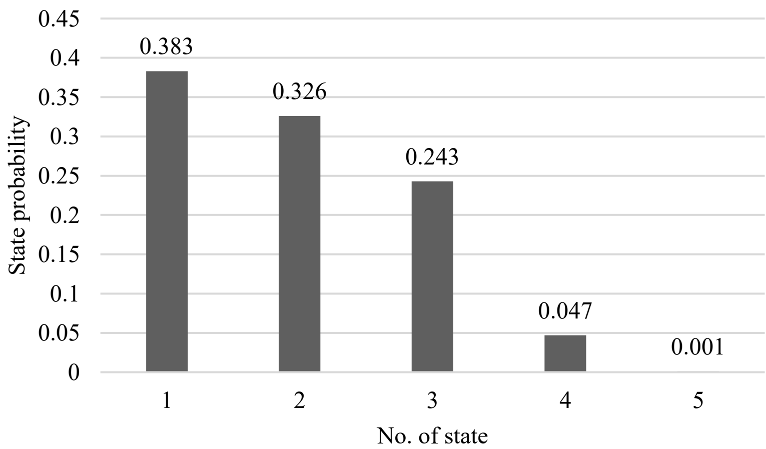

Figure 5 – Probability of occurrence of states

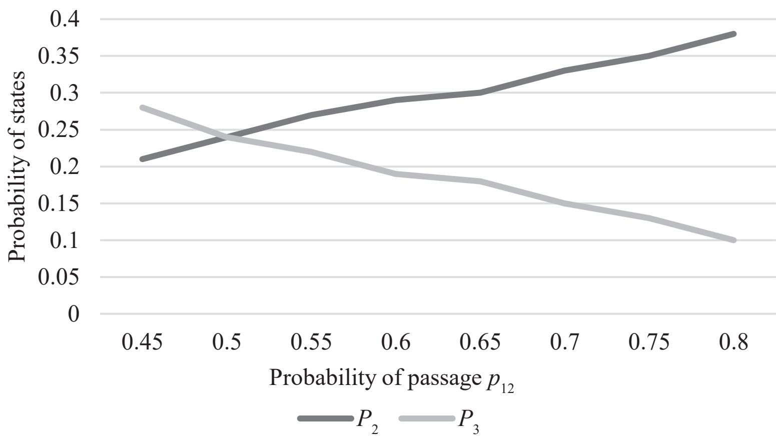

Figure 6 – Change in the occurrence of the state of transhipment

An interesting comparison is the graph shown in *Figure 6*, which shows how the incidence of manipulations increases with the probability of occurrence of a transition from the standstill state to manipulations while maintaining the other transition intensity parameters.

It can also be interpreted the other way around, i.e. a reduction in the number of unproductive manipulations will lead to an increase in the occurrence of the productive manipulations, in the state of transhipment.

5. CONCLUSIONS

Although the literature on maritime and inland container terminals is quite extensive, there is no single coherent method to comprehensively address the issues of reducing unproductive manipulations of handling equipment with respect to states of maintenance and repairs. This is due to the peculiarities of container types, storage methods as well as the information flow. The latter aspect appears to be the factor most strongly influencing the accuracy of planning the distribution of containers at the right storage allocation.

The studies presented are used to assess the efficiency of terminal operations. They allow the probability of unproductive manipulations to be determined, which can be the starting point for taking measures to reduce these states. It has been shown that the probability of moving to productive manipulations, such as transhipment, rather than to 'yard work', increases the total time spent in a productive state. Furthermore, it affects the relationship between fuel consumption resulting from the number of container operations.

The model assumes a mathematical model based on a semi-Markov process. As an analytical method, it is a tool in which probability distributions of transitions between states can be freely applied. It can be somewhat problematic to prepare the data because, for example, different types of maintenance and repair activities have to be interpreted – classifying them into manipulations accordingly.

The advantage of this type of modelling is the possibility of adding such states that are needed from the analyst's point of view. It is possible, for example, to extend the model with such states, which will make it possible to analyse the number of unproductive manipulations related to the handling of empty/full containers, where a specific consignee is involved, belonging to selected shipowners, of various sizes etc. Expanding the model will then make it necessary to complete the statistical database and prepare further input data.

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Określanie prawdopodobieństwa nieproduktywnych manipulacji podczas operacji lądowego terminalu intermodalnego

Streszczenie
Artykuł dotyczy metody określania prawdopodobieństwa nieproduktywnych manipulacji podczas operacji, konserwacji lub napraw na lądowym terminalu intermodalnym. Metoda ta opiera się matematycznie na procesie semi-Markowa. Opracowana metoda umożliwia rewizję częstotliwości nieproduktywnych manipulacji oraz ich trwania. Razem daje to możliwość analizy i zmiany operacji wewnętrznego terminalu na bardziej produktywne.

Słowa kluczowe
optymalizacja składowania kontenerów; terminal intermodalny; składowanie kontenerów; procedura heurystyczna; model semi-Markowa.