EVENT-B MODEL FOR INCREASING THE EFFICIENCY OF WAREHOUSE MANAGEMENT

Hrušecká D., Adla R., Krayem S., Pivnička M.*

Abstract: With raising customers' requirements and competition forces, companies face the pressure to increase both the efficiency and flexibility of production and logistic processes thatdirectly influences their management activities. This article deals especially with the processes related to chaotic storage systems using automated high bay warehouse technologies operated by traditional automated crane-based storage and retrieval systems (AS/RS) that have become popular in recent years as systems supporting the lean management philosophy in accordance with growing requirements of the fourth industrial revolution. Presented proof obligation Event-B model includes advanced algorithms for automated storage and retrieval warehouse activities that should ensure the higher efficiency and flexibility of both logistic and all consequent processes. The algorithms are based on the idea of continuous relocation of stored items during an automated stacker crane´s idle times in order to ensure faster delivery of future orders from better accessible positions. It supports automated decision-making in warehouse management systems in accordance with lean principles. The proposed solution was verified by experimental model processed by a discrete even simulation software, which confirmed its positive impact on the flexibility of storage and retrieval activities. Its implementation into the real practice increases the accuracy of warehouse management processes which directly influence the production management and other decision-making activities.

Key words: Event-B method, Warehouse Management, Production Management, Automated Decision Making, Automatic High Rack Stacker, Discrete Event Simulation

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Introduction

The pressure on lean production with minimum wastes prevails in many industrial companies not merely in automotive industry. Along with the current trend of increasing automation and digitization in the spirit of Industry 4.0, it places higher demands on logistic activities that can significantly influence production process performance. As Synáková (2017) states, many production systems are subject to tight capacity constraints and logistics must be able to ensure its smooth running. Also the role of industrial engineering has changed. Besides the labour productivity improvement, it has to focus on smart control algorithms of automated production

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and logistic systems that ensures efficient management of selected processes and productive interaction among technology, human resources and the whole production and logistic surroundings.

In order to ensure lean warehousing and flexible demand response, automated high bay warehouses have become popular choices not even for logistics and distribution centres, but also for many manufacturing companies. The main advantages of automated high bay warehouses with automated storage and retrieval systems lay in their high capacity combined with a relatively small ground plan, high utilization ensured by chaotic system of units´ storing and relatively low time of one storage or retrieval cycle (Jerman et al., 2017). Especially in mini-load warehouses, automated crane-based storage and retrieval systems are accompanied by shuttle based storage and retrieval systems that can help to achieve both low operational costs and large volume flexibility (Tappia et al., 2016).

There is no doubt that automated high bay warehouses and automated storage and retrieval systems, regardless of special type and used technology, provide the companies with several significant advantages including the efficient utilization of warehouse space, costs savings in form of lower number of warehouse workers, reduction of damages and losses and better inventory control (Lerher, 2016). However, the technology itself is not sufficient for system improvement. In order to ensure higher effectiveness and efficiency of warehouse system, the control mechanisms of AS/RS must be precisely adapted to existing conditions, priorities and set goals. This contribution focuses on the problem of AS/RS machine´s response time that can be shortened through smartly defined control algorithms. For this purpose, Event-B method has beenused because of its fault-free structure and high potential for modelling complex systems. The main goal is to propose a proof obligation based control model that should help to decrease an average response time of AS/RS machine. The model is subsequently evaluated through a discrete-event simulation based experiment.

Automated Storage and Retrieval Systems

Inventory management is the major issue not even in individual industrial companies, but across the whole supply chain and many researchers deal with warehouse or inventory optimization problems. For example, Mahamani et. al (2007) proved the benefits of the single item inventory replenishment policy through their case study. However, increasing flexibility of logistic and inventory management systems often causes higher logistic costs. Advanced technologies and software tools help to improve both of above key performance logistic indicators, but they also require a precise management and evolution.

As Kovács and Kot (2016) in their study has pointed out that fast changing market environment and fluctuating demand increases requirements to flexibility and efficiency of logistic processes. Bortolini et al. (2017) confirm this statement that efficiency and effectiveness of the warehouse design and logistic operations play a significant role for improving an enterprise´s competitiveness.

In connection to the above mentioned requirements of higher flexibility, the concept of Industry 4.0 is getting a global recognition in all business activities. Belov (2016) explains the fourth industrial revolution as a new paradigm that involves the integration of Cyber Physical Systems in production and logistic processes by connecting the machines, tools, warehouses, logistic equipment, decision-making systems etc. and ensuring the independent data exchange among them. In the context of Industry 4.0, many companies have implemented automated technologies not just in manufacturing area, but also for managing warehouse operations. However, the technology itself is not sufficient. Storage assignment and operation rules have a great impact on the performance of automated storage and retrieval systems as Gu et al. (2010) prove in their study. Another aspect is the relationship between AS/RS technology and other material handling systems that gets a little attention in many cases as Kalyanaraman and Keerthika (2016) emphasize.

Many authors deal with the problem of minimizing the response time of AS/RS machines in automated storage systems. For example a model for the performance evaluation and design of AS/RS machine which allows for the proportions of stored units in relation to the physical parameters of the warehouse space. In contrast to many other researches, the algorithm of Soyaslan et al. (2017) considers even the least energy consuming route besides its length as well as the studies of Bortolini et al. (2017) or Jerman et al. (2017). Very interesting approach is presented by Yue et al. (2017) who propose a slotting optimization model for AS/RS based on genetic algorithms in order to minimize response time of AS/RS machine. Despite a plenty of studies deal with the problem of AS/RS machine response time optimization, none of them come up with the idea of continuous warehouse space re-arrangement during AS/RS machine idle times.

Event-B Method

Event-B is a formal refinement based method used for system-level modelling. It uses a set theory as a modelling notation. Using its refinement tool enables to represent systems at different abstraction levels. The greatest benefit of Event-B modelling in comparison to other methods is its mathematical proof used to verify consistency between refinement levels. That is why Event-B method has been widely used in major safety-critical systems like fire alarms, emergency services and others (Abrial et al., 2010a).

Event-B model consists of two basic sections: context and machine (or more machines). Context includes a set of constants and their axioms while machine consists of a set of variables and invariants describing individual events. Event represents a guarded command initializing some actions. Each event can be executed only when all its guards are true (Abrial et al., 2010a; Hrušecká, 2016). Despite the fact that Event-B language has many advantages in comparison to standard programming languages, its non-determinism and implicit control flow have several shortcomings related especially to the lack of code-like structure.

However, some researchers have developed different support tools and rules that help to overcome the most critical shortcomings and simplify to refine the abstract machine structure to a specific level (Dalvandi et al., 2017; Mashkoor et al., 2017)
Another advantage of Event-B method is the possibility to cut a single refined model into several almost independent pieces. This is useful especially in case of very complex systems when the model has to be more and more refined and it becomes impossible to manage all its state variables and transitions as a whole (Abrial, 2010b).

Methodology

The main goal of the study is to propose a proof obligation based model for controlling an AS/RS machine in such a way that its average response time decreases. As mentioned above, the key determinants of lean production are changing with a growing automation of manufacturing and logistics processes. Regarding this fact, our solution offers a model for increasing the efficiency of logistic processes through shortening the response rate of automated warehouse technologies. Used methodology is adopted from classic industrial engineering approach used for manual processes´ optimization. It means that individual types of waste were identified at first. In case of automated high bay warehouse system, the most critical types of waste that occur the most often are waiting for the new order and long transport distances influencing the response rate. All other types of waste are irrelevant in relation to the AS/RS machine control system. On that account, presented model brings solution for eliminating the most critical types of waste.
In this context, the study has set the following hypothesis, which is evaluated through a discrete-event simulation, multiple experiments:

— *H1: Proposed model, based on the idea of transferring badly accessible pallet units closer to the AS/RS default position (depot) during its idle times, helps to improve the average time of order´s execution in a single-deep high bay WH.*

Event-B methods was chosen for process modelling because of its possibility to use refinement to represent described system at different abstraction levels and mathematical proofs to verify consistency between all refinement levels (Abrial, 2010b). This approach is very beneficial for complex systems, because it enables quite clear and easy modelling based just on set theory and mathematical notations. Moreover, despite its predefined set of guards per each refinement level, it offers a strong fault-free solution.
Proposed solution was tested in form of discrete-event simulation experiment with random inputs. The experimental model consists of one 100 meters long and 40 meters high single-deep high bay rack operated by AS/RS machine with an average speed of 0.5 meters per second. The maximum capacity of the rack is 4000 pallet units. It was replenished periodically in 12 hours' intervals with a batch of 40-50 pallet units. Retrieval orders come from production lines in random manner with average interval of 10 minutes and standard deviation of 2 minutes. In order to evaluate the set hypothesis, 6 simulation runs were used per each of two different

experiments: with allowed/not allowed pallet units´ transfers during the AS/RS machine idle times. Each simulation run represents a non-stop 10-days operation time. The execution time of each order was measured during all experiments. Afterwards, acquired data were statistically evaluated and tested in order to prove these hypothesis.

Results: Event-B Model

Presented model considers single-deep high bay racks operated by AS/RS machines with the load capacity of one unit. In order to improve the AS/RS response time, the study has proposed a model that ensures all units are always stored as close to the AS/RS default position (depot) as possible. This condition is fulfilled through transferring badly accessible pallet units closer to the depot during the AS/RS machine idle times. Through its pre-set criteria and automatically guarded events, it helps to automate decision making in logistic ensuring the positive impact to production management.
Event-B method is very useful especially in that situation when the abstraction of complex interactions between the system components and their mathematical verification is highly beneficial (Abrial et al., 2010a). In the first step of Event-B modelling, a set of constants and their axioms (called "context") must be defined. In this case, the initial context structure is as follow:

```
CONTEXT    C0
   SETS
           Rack
           Place_status
CONSTANTS
           Available          // storage position is empty
           Not_Available      // storage position is occupied
  AXIOMS
           axm1: partition(Place_status, {Available}, {Not_Available}
     END
```

After defining the model context, all variables, invariants and specific events all possible status changes must be mathematically described. First of all, the abstract machine with very simple general events is created and all model variables are given an initial value. All other events include different changes of the model status:

```
  MACHINE    M0
     SEES    C0
VARIABLES
             Units           // pallet units
             Unit_place    // storage position of selected unit
```

Storage_places // the rack is divided into storage positions as Array
Best_place // storage position with the shortest response time

INVARIANTS

inv1: $Unitss \subseteq Rack$
inv2: $Unit\_place \in Units \rightarrow \mathbb{N}$
inv3: $Storage\_places \in \mathbb{N} \rightarrow Place\_Status$
inv4: $Best\_place \in \mathbb{N}$

EVENTS

Initialization

BEGIN

act1: $Units := \emptyset$
act2: $Unit\_place := \emptyset$
act3: $Storage\_places :\in \mathbb{N} \rightarrow \{Available\}$ *// all positions are empty*
act4: $Best\_place :\in \mathbb{N}$

END

Store Unit *// the first real event = storing the new unit*

ANY

u // new pallet unit

WHERE

grd1: $u \notin Units$

THEN

act1: $Units := Units \cup \{u\}$
act2: $Unit\_place(u) := 0$ *// unit position is (0), store the new unit*

END

Transfer Unit to the Better Accessible Empty Position

ANY

u

WHERE

grd1: $u \in Units$
grd2: $Unit\_place(u)=0$ *// stored unit*
grd4: $Best\_place \in \mathbb{N}$
grd5: $Storage\_places(Best\_place)=Available$
grd6: $\forall x \cdot x \in \mathbb{N} \wedge Storage\_places(x)=Available \Rightarrow Best\_place \leq x$

THEN

act1: $Unit\_place(u) := Best\_place$
act2: $Storage\_places(Best\_place) := Not\_Available$

END

Retrieve Unit

ANY

u

WHERE

grd1: $u \in Units$

THEN

act1: Storage_places(Unit_place(u)) ≔ Available
act2: Unit_place ≔ {u} ⩤ Unit_place
act3: Units ≔ Units \ {u}
END

In order to make thismodel more precise and closer to reality, refinement of the above described basic events including more variables and details was created in the subsequent steps. Due to its vastness, the studypresents just example of refinement for the first two events (Initialization and Store Unit):

MACHINE M1
REFINES M0
SEES C0
VARIABLES
Units, Unit_place, Storage_places, Unit_Quantity, Best_place
INVARIANTS
inv1: Units ⊆ Rack
inv2: Unit_place ∈ Units → ℕ
inv3: Storage_places ∈ ℕ → Place_status
inv4: Unit_Quantity ∈ Units → ℕ1
inv5: Best_place ∈ ℕ
EVENTS
Initialization
BEGIN
act1: Units ≔ ∅
act2: Unit_place ≔ ∅
act3: Storage_places :∈ ℕ → {Available}
act4: Unit_Quantity ≔ ∅
act5: Best_place :∈ ℕ
END
Store New Unit
REFINES
Store Unit
ANY
u // pallet unit
q // quantity
WHERE
grd1: u ∉ Units
grd2: q ∈ ℕ1
THEN
act1: Units ≔ Units ∪ {u}
act2: Unit_place(u) ≔ 0
act3: Unit_Quantity(u) ≔ q
END

Simulation Based Experiment and Model Evaluation

Above described Event-B model for controlling AS/RS machine in order to shorten average retrieval cycle times was evaluated through a discrete-event simulation model constructed in software application Tecnomatix Plant Simulation. The model consists of one single-deep high bay rack, one AS/RS machine, one production line demonstrating the requirements of customers (sending signals for pallets´ retrievals) and plenty of methods used for the model´s control representing the above mentioned management principles.

This study has simulated a non-stop 10-days operation time with 6 simulation runs under each of two experiments. The only difference between the experiments lays in allowed/not allowed items´ transfers during the AS/RS machine idle times. For modelling cycle times of incoming orders, the uniform distribution with an average time of 10 minutes and standard deviation of 2 minutes was used. Statistics of output values at the confidence level equal to 95% are presented in Table 1.

Table 1. Statistical Evaluations

	Experiment 1 (transfers allowed)	Experiment 2 (without transfers)	Difference (Exp 2 – Exp 1)
Average time of one order´s execution (sum of all runs)	3:44.093*	3:50.753	↓ 6.660
Standard deviation	2.544	3.259	↓ 0.715
Minimum average time	3:41.806	3:47.710	↓ 5.904
Maximum average time	3:46.833	3.54.191	↓ 7.358
Left interval bound	3:37.774	3:42.658	↓ 4.884
Right interval bound	3:50.412	3:58.848	↓ 8.436
**Values are in form MM:SS.sss (minutes, seconds and milliseconds)*			

The p-value of the T-test of average times of order´s execution is 0.053, which is higher than the most often used level of significance of 0.05. Therefore, we cannot presume that the mean values are different. However, the result is significant at 0.10 level of significance. That is why, we can accept the hypothesis that the proposed model helps to improve average time of order´s execution in a single-deep high bay warehouse with a probability of 90%. Moreover, the results described in Table 1 demonstrates moderate decrease in all measured time values while implementing the idea of presentment Event-B model into practice (transferring storage units during the AS/RS machine idle times). Especially in case of standard deviation, we can notice the decrease of more than 20%, what is quite significant improvement for more accurate forecasting and planning of retrieval activities influencing the subsequent processes.

Discussion

In many cases, the problem of demand forecasting is the biggest enemy of production process performance. Kim et al. (2018) has proposed the model for improving warehouse labor efficiency by intentional forecast bias. Their model can be transferable to the problem of this study, but it presumes the possibility to forecast demand changes what is very difficult in many cases. Maschietto et al. (2016) solve a very similar problem to ours when proposing a genetic algorithm based model to address a two cranes scheduling problem, but without a direct interaction with production process management and its changing and unpredictable requirements. Sapurto and Rouyendegh (2016) deal with the question of appropriate material handling equipment for warehouse operations what is another variable influencing not only the flexibility of logistic operations, but also the cost management.

In comparison to other researches, this study focuses on automated decision making in any situation based on predefined criteria. It helps to automate logistic management decision making activities and improve its flexibility in fulfilling the requirements of production processes in order to ensure their smooth running. More specifically, the study has aimed to propose an algorithm for controlling AS/RS machine in such a way that would reduce AS/RS machine response time and increase its flexibility. The presented solution is built on the idea of continuous warehouse space re-arrangement and transferring the worst accessible storage units closer to AS/RS default position (depot station) during its idle times. Above described algorithm is modelled in Event-B language as we consider it as the most suitable method for solving such a complex problem. To confirm the above hypothesis, that presented Event-B model really improves the average time of order´s execution, the study performed several experiments using a discrete-event simulation software tool. The hypothesis was confirmed at 0.10 level of significance. The energy consumption was not included into evaluation of the model what can be considered as a limitation of our study in comparison of Jerman et al. (2017) or Bartolini et al. (2017). Combining those results with the solution of this study, it could achieve even a more reasonable and more complex solution applicable in practice.

Conclusion

For production managers, logistic processes are ones of the critical variables highly influencing the performances of the whole production. The common problem in manufacturing companies lies in separated logistic and production management decision making activities. In the spirit of Industry 4.0, many companies start to implement advanced digital technologies supporting the management of selected processes. However, the technology itself is not sufficient and it requires the high level of interaction between the human expertize, software algorithms and daily production problems. The Event-B model described in this article shows how these interactions should work. Event-B method is not just a simple programming language. Because of its proof obligatory mechanisms, it is able to manage any process based on set limitations and goals. It substitutes process manager and propose the most sufficient solutions in every situation.

Despite the fact that Event-B method is usable in extremely complex situations, presented model has some limitations, especially the fact that authors focused on ensuring the highest possible response time of AS/RS machine and do not consider other cost sources such as energy consumption, maintenance or depreciation. In the future research, the topic will be extended to other management problems related to increasing automation and digitization of logistic and production processes, such as automated supplying of production lines using AGV technologies (Automatic Guided Vehicles), expert systems in production planning area or smart supply chain management.

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MODEL EVENT-B DLA ZWIĘKSZENIA EFEKTYWNOŚCI ZARZĄDZANIA HURTOWNIĄ

Streszczenie: Wraz z podnoszeniem wymagań klientów i siłami konkurencji, przedsiębiorstwa napotykają presję, aby zwiększyć zarówno wydajność, jak i elastyczność procesów produkcyjnych i logistycznych, co bezpośrednio wpływa na ich działania zarządcze. Artykuł dotyczy w szczególności procesów związanych z chaotycznymi systemami magazynowania wykorzystującymi zautomatyzowane technologie magazynowe wysokiego składowania obsługiwane przez tradycyjne zautomatyzowane systemy magazynowania i wyszukiwania oparte na dźwigach (AS / RS), które stały się popularne w ostatnich latach jako systemy wspierające filozofię lean management zgodnie z rosnącymi wymaganiami czwartej rewolucji przemysłowej. Zaprezentowany dowód certyfikacji, Model Event-B, zawiera zaawansowane algorytmy do zautomatyzowanego przechowywania i wyszukiwania działań magazynowych, które powinny zapewnić wyższą wydajność i elastyczność zarówno procesu logistycznego, jak i wszystkich powiązanych procesów. Algorytmy opierają się na idei ciągłego przemieszczania przechowywanych przedmiotów w czasie bezczynności automatycznych dźwigów ładunkowych w celu zapewnienia szybszego dostarczania przyszłych zamówień z lepiej dostępnych pozycji. Obsługuje automatyczne podejmowanie decyzji w systemach zarządzania magazynem zgodnie z zasadami lean. Proponowane rozwiązanie zostało zweryfikowane za pomocą modelu eksperymentalnego przetworzonego przez dyskretne oprogramowanie symulacyjne,

które potwierdziło jego pozytywny wpływ na elastyczność działań związanych z przechowywaniem i odzyskiwaniem. Jego wdrożenie w rzeczywistą praktykę zwiększa dokładność procesów zarządzania magazynem, które bezpośrednio wpływają na zarządzanie produkcją i inne działania decyzyjne.
Słowa kluczowe: metoda Event-B, zarządzanie magazynem, zarządzanie produkcją, automatyczne podejmowanie decyzji, automatyczna układarka wysokiego składowania, dyskretna symulacja zdarzeń

提高仓库管理效率的事件B模型

摘要：随着客户需求和竞争力的提升，企业面临着提高直接影响其管理活动的生产和物流过程的效率和灵活性的压力。本文尤其涉及与传统的基于起重机的自动化存储和检索系统（AS/RS）运行的自动化高架仓库技术相关的混沌存储系统的相关流程，这些系统近年来已成为流行的支持精益管理理念的系统随着第四次工业革命的要求越来越高。提供证明义务事件-B模型包括自动化存储和检索仓库活动的高级算法，这些算法应确保物流和所有后续流程的效率和灵活性更高。该算法基于在自动堆垛机空闲时间期间对存储物品进行连续重新定位的想法，以确保从更好的可访问位置更快地交付未来订单。它根据精益原则支持仓库管理系统中的自动化决策。所提出的解决方案通过由离散均匀仿真软件处理的实验模型进行验证，该模型证实了其对存储和检索活动的灵活性的积极影响。将其实施到实际操作中会提高仓库管理流程的准确性，这直接影响生产管理和其他决策活动。
关键词：事件B方法，仓库管理，生产管理，自动决策，自动高架堆垛机，离散事件模拟。