DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

Meta-model for calculating the mean energy demand of automated storage and retrieval systems

Metamodell zur Berechnung des mittleren Energiebedarfs von automatischen Kleinteilelagern

Rainer Ertl
Willibald A. Günthner

Lehrstuhl für Fördertechnik Materialfluss Logistik
Technische Universität München

Energy efficiency has come to be an important research topic in intralogistics. Special focus is placed on automated storage and retrieval systems (AS/RS) utilizing stacker cranes as these systems are very popular and consume a significant portion of the total energy demand of intralogistical systems. Numerical simulation models were developed to calculate the energy demand for discrete single and dual command cycles. However these simulation models are not suitable to perform fast calculations to determine a mean energy demand value of a complete storage aisle.

For this purpose analytical approaches would be more appropriate but until now analytical approaches only deliver results for certain configurations. In particular, for commonly used stacker cranes, equipped with an intermediate circuit connection within their drive configuration, there is no analytical approach available to calculate the mean energy demand. This article addresses this research gap and presents a calculation approach which provides planners of storage systems a quick calculation of the energy demand.

[Keywords: energy demand, regression, multivariate methods of analysis, automated storage and retrieval systems, intermediate circuit connection]

Energieeffizienz hat sich zu einem wichtigen Forschungsthema im Bereich der Intralogistik entwickelt. Der Fokus liegt dabei insbesondere auf automatischen Kleinteilelagern (AKL) mit Regalbediengeräten, da diese Systeme weit verbreitet sind und einen deutlichen Anteil am Gesamtenergiebedarf intralogistischer Systeme haben. Numerische Simulationsmodelle wurden erstellt, mit welchen der Energiebedarf für bestimmte Einzel- oder Doppelspiele relativ genau berechnet werden kann. Allerdings eignen sich diese Simulationsmodelle nur eingeschränkt zur schnellen Berechnung des mittleren Energiebedarfs für eine komplette Lagergasse. Hierzu wären analytische Ansätze besser geeignet, wobei bislang solche Ansätze nur für bestimmte Konfigurationen verfügbar sind. Insbesondere für die heute übliche Ausrüstung der Regalbediengeräte mit Zwischenkreiskopplung innerhalb der Antriebskonfiguration gibt es keinen analytischen Ansatz zur Berechnung des mittleren Energiebedarfs. Dieser Aufsatz soll sich mit dieser Forschungslücke beschäftigen und einen Berechnungsansatz aufzeigen, die es dem Planer ermöglicht den Energiebedarf dieser Systeme schnell zu berechnen.

[Schlüsselwörter: Energiebedarf, Regression, Multivariate Analysemethoden, Automatisches Kleinteilelager, Zwischenkreiskopplung]

1 INTRODUCTION

The Climate change, increasing energy costs, more stringent legal restrictions and not least marketing aspects have made energy efficiency a key issue for intralogistics. This has an impact on the requirements of logistical systems and thus on conveyors such as stacker cranes in automated storage and retrieval systems (AS/RS).

A large number of developments and investigations in the field of intralogistics aim at reducing the energy demand of these systems in operation. Constructive-technical [EG12, FL11, Wah12, Wah14] and organizational-strategical [EG13a, Sch14, Som14, MM14] methods have key priority. Lightweight frame structure concepts, energy efficient path finding algorithms and energy optimized allocation strategies have led to a reduction of the energy demand of these systems within the last years.

An appropriate measure for evaluating different configurations and for cost planning is the mean energy demand. Several simulation models are available for calculating the energy demand of automated storage and retrieval systems [GSEH11, BLSF12, SSTSZ13, MM13]. These simulation models enable a realistic consideration of individual features and stock configurations, so the en-

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

ergy demand in operation can be calculated for particular single or double cycles.

However, the computation of complex numerical models is very time consuming, so it is only in a minor degree suitable for large parameter studies [SBH10]. The simulation approach delivers a case-specific result, which does not allow any universal quantitative statements or conclusions to other configurations.

On the other hand, analytical approaches are a potential solution for a fast calculation of the mean energy demand [EG13b, HEG13, LER14]. For example conditional equations for energy saving of stacker cranes in AS/RS equipped with an energetic recovery system are available. But significantly there is no comparable approach for calculating the mean energy demand for the most widespread drive configuration of stacker cranes, the linkage of intermediate circuit between horizontal and vertical drive.

2 RESEARCH OBJECTIVE AND METHODICAL APPROACH

In this article a methodical approach is presented for the quick calculation of the mean energy consumption of stacker cranes (AS/RS). Particularly, the main focus is to develop a method for the fast calculation of the mean energy demand of stacker cranes with intermediate circuit connection. A further aim is to quantify the relevant parameters influencing the energy consumption of such stacker cranes.

In AS/RS utilizing stacker cranes with intermediate circuit connection the recoverable power of one drive is provided to the other drive with a current energy demand. This exchange of electric energy with an intermediate circuit connection is only possible, when the energy demand of one drive is simultaneous to the energy recovery of the other drive. If the recovered energy is available at a time, when there is no energy demand in other drives, this energy is transferred into heat in a break resistor.

As analytical calculation approaches are not possible for this configuration, a calculation model will be generated based on simulation experiments using multivariate methods of analysis. Therefor the following methodical approach is applied:

1. Calculation of the mean energy demand with sufficient precision in simulation experiments by taking a random sample from the population.
2. Creating a data base for the mean energy demand by use of simulation and statistical design of experiments.
3. Deducing a meta-model by applying multivariate analysis methods.
4. Interpretation of the results.

3 SIMULATION MODEL

Stacker cranes in automated storage and retrieval systems are moving along three axis. There is a horizontal drive to travel along the warehouse aisle and a vertical drive to lift the load handling device. The load handling device itself is in charge of storing and retrieving loading units from and into the rack shelves.

The simulation model calculates the energy consumption of the automated storage and retrieval system in the following steps [EG13a]:

- Calculating the trajectories of the horizontal and vertical drive
- Calculating the power requirement of each drive
- Calculating the resulting energy demand considering the energy management (such as intermediate circuit connection)

The movement of the stacker crane in horizontal and vertical direction is calculated as a 7-phases-motion taking into account the jerk of the drives. Figure 1 illustrates the modelling of the movement of a single drive with full 7-phases-motion. There are four phases with constant jerk, two phases with constant acceleration and one phase with constant velocity.

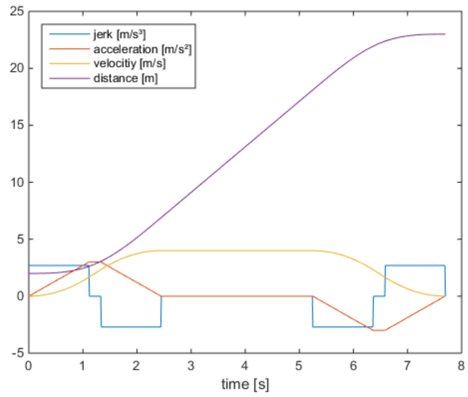


Figure 1. Full 7-phases-motion of a single drive [GSEH11]

The calculation of the trajectories includes algorithms for cases when the maximum speed or the maximum acceleration can not be reached, because of short travelling distances.

Especially concerning the requirements of stacker cranes with intermediate circuit the trajectories of horizontal and vertical drives are synchronized as described by Ertl and Günthner [EG13a]. For example, if the horizontal movement takes more time than the vertical movement and the vertical movement is a lifting task, the lifting will be delayed for an optimal exchange of energy. By this intervention it is ensured that the recoverable

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

braking energy of the horizontal drive can be utilized directly for the energy consuming lifting task.

With knowledge of the trajectories and the drive parameters listed in Table 1 the power requirement $P_D(t)$ for a drive can be calculated as follows:

$$P_D(t) = M_D(t) \cdot \omega_D(t)$$

With:

$$M_D(t) = M_T(t) + M_R(t) + M_F(t) + M_L(t)$$

$$\omega_D(t) = v(t) \cdot \frac{2}{d_D} \cdot i_D$$

Table 1. Parameters for calculation of the energy demand

Label	description	unit
$\boldsymbol{P_D(t)}$	Power requirement of a drive	$[W]$
$\boldsymbol{M_D(t)}$	Torque of a drive	$[Nm]$
$\boldsymbol{\omega_D}$	Spin velocity of a drive	$[s^{-1}]$
$\boldsymbol{M_T(t)}$	Translational torque of a drive	$[Nm]$
$\boldsymbol{M_R(t)}$	Rotational torque of a drive	$[Nm]$
$\boldsymbol{M_F(t)}$	Torque by friction of a drive	$[Nm]$
$\boldsymbol{M_L(t)}$	Load torque of a drive	$[Nm]$
$\boldsymbol{v(t)}$	Horizontal or vertical velocity	$[\frac{m}{s}]$
$\boldsymbol{d_D}$	Diameter of the downforce	$[m]$
$\boldsymbol{i_D}$	Gear ratio of a drive	$[-]$
$\boldsymbol{\eta_D}$	Efficiency of the drive	$[-]$
$\boldsymbol{P_x(t)}$	Power requirement of the horizontal drive	$[W]$
$\boldsymbol{m_x(t)}$	Moved mass in horizontal direction	$[kg]$
$\boldsymbol{a_x(t)}$	acceleration of the horizontal drive	$[\frac{m}{s^2}]$
$\boldsymbol{d_x}$	Diameter of the downforce of the horizontal drive	$[m]$
$\boldsymbol{i_x}$	Gear ratio of a horizontal drive	$[-]$
$\boldsymbol{\eta_x}$	Efficiency of the horizontal drive	$[-]$
$\boldsymbol{J_x}$	Total moment of inertia of the horizontal drive referred to the engine	$[kgm^2]$
$\boldsymbol{f_x}$	Coefficient of friction of the horizontal drive	$[-]$
$\boldsymbol{v_y(t)}$	velocity of the vertical drive	$[\frac{m}{s}]$
$\boldsymbol{P_y(t)}$	Power requirement of the vertical drive	$[W]$
$\boldsymbol{m_y(t)}$	Moved mass in vertical direction	$[kg]$
$\boldsymbol{a_y(t)}$	acceleration of the vertical drive	$[\frac{m}{s^2}]$
$\boldsymbol{d_y}$	Diameter of the downforce of the vertical drive	$[m]$
$\boldsymbol{i_y}$	Gear ratio of a vertical drive	$[-]$
$\boldsymbol{\eta_y}$	Efficiency of the vertical drive	$[-]$
$\boldsymbol{J_y}$	Total moment of inertia of the vertical drive referred to the engine	$[kgm^2]$
$\boldsymbol{v_y(t)}$	velocity of the vertical drive	$[\frac{m}{s}]$
$\boldsymbol{f_y}$	Coefficient of friction of the vertical drive (converted with reference to weight force instead of normal force)	$[-]$
$\boldsymbol{\eta_{ZW}}$	Efficiency of energy exchange in intermediate circuit	$[-]$
$\boldsymbol{P_0}$	Base load consumption	$[W]$
$\boldsymbol{P_{0,red}}$	Reduced base load consumption	$[W]$

For the horizontal drive the torque $M_x(t)$ and the power requirement $P_x(t)$ are calculated for $v_x(t) \geq 0 \wedge a_x(t) \geq 0$ as follows:

$$M_x(t) = m_x(t) \cdot a_x(t) \cdot \frac{d_x}{2} \cdot \frac{1}{i_x} \cdot \frac{1}{\eta_x} + J_x \cdot \dot{\omega}_x(t) + f_x \cdot m_x(t) \cdot g \cdot \frac{d_x}{2} \cdot \frac{1}{i_x} \cdot \frac{1}{\eta_x}$$

$$P_x(t) = \frac{1}{\eta_x} \cdot m_x(t) \cdot a_x(t) \cdot v_x(t) + J_x \cdot \dot{\omega}_x(t) \cdot \frac{2}{d_x} \cdot i_x + \frac{1}{\eta_x} \cdot f_x \cdot m_x(t) \cdot g \cdot v_x(t)$$

For the vertical drive the torque $M_y(t)$ and the power requirement $P_y(t)$ are calculated for $v_y(t) \geq 0$ as follows:

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

$$M_y(t) = m_y(t) \cdot a_y(t) \cdot \frac{d_y}{2} \cdot \frac{1}{i_y} \cdot \frac{1}{\eta_y} + J_y \cdot \dot{\omega}_y(t) + (1 + f_y) \cdot m_y(t) \cdot g \cdot \frac{d_y}{2} \cdot \frac{1}{i_y} \cdot \frac{1}{\eta_y}$$

$$P_y(t) = \frac{1}{\eta_y} \cdot m_y(t) \cdot a_y(t) \cdot v_y(t) + J_y \cdot \dot{\omega}_y(t) \cdot \frac{2}{d_y} \cdot i_y + \frac{1}{\eta_y} \cdot (1 + f_y) \cdot m_y(t) \cdot g \cdot v_y(t)$$

The energy management with intermediate circuit connection is modelled as follows:

For $P_x(t) \geq 0$ and $P_y(t) \geq 0$:

$$E_{ZW}(t) = \int P_x(t) + P_y(t) + P_0 dt$$

For $P_x(t) \geq 0$ and $P_y(t) < 0$ and $P_x(t) + \eta_{ZW} \cdot P_y(t) \geq 0$:

$$E_{ZW}(t) = \int P_x(t) + \eta_{ZW} \cdot P_y(t) + P_0 dt$$

For $P_x(t) \geq 0$ and $P_y(t) < 0$ and $P_x(t) + \eta_{ZW} \cdot P_y(t) < 0$:

$$E_{ZW}(t) = P_{0,red} \cdot t$$

For $P_x(t) < 0$ and $P_y(t) \geq 0$ and $\eta_{ZW} \cdot P_x(t) + P_y(t) \geq 0$:

$$E_{ZW}(t) = \int \eta_{ZW} \cdot P_x(t) + P_y(t) + P_0 dt$$

For $P_x(t) < 0$ and $P_y(t) \geq 0$ and $\eta_{ZW} \cdot P_x(t) + P_y(t) < 0$:

$$E_{ZW}(t) = P_{0,red} \cdot t$$

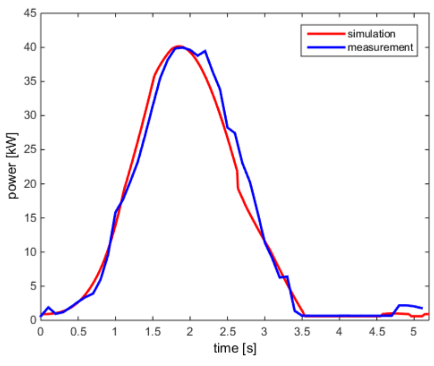
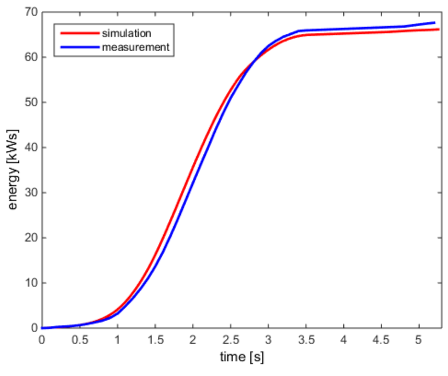
For $P_x(t) < 0$ and $P_y(t) < 0$:

$$E_{ZW}(t) = P_{0,red} \cdot t$$

The energy demand E_{LH} during the load handling process is calculated with help of a mean power demand P_{LH} during load handling, which is independent from the position in the rack.

$$E_{LH} = P_{LH} \cdot t_{LH}$$

The simulation model was validated by matching simulation results to measured data at various real systems. The samples in figure 2 illustrate the comparison for two different test runs at an automated storage and retrieval system (length: 22 m, height: 7.5 m, total mass: 2 t, live load: 100 kg). Figure 2 proves only small deviations between simulation results and measured values.

<table>
<tr><th>Test run</th><th>Power requirement [kW]</th><th>Energy demand [kWs]</th></tr>
<tr><td>$\Delta x = 12m$
$a_x = 3\frac{m}{s^2}$
$v_x = 6\frac{m}{s}$
$\Delta y = 6.7m$
$a_y = 3\frac{m}{s^2}$
$v_y = 3\frac{m}{s}$</td><td>
</td><td>
</td></tr>
</table>

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

$$\Delta x = 21m \quad a_x = 3\frac{m}{s^2} \quad v_x = 4\frac{m}{s} \quad \Delta y = 6.7m \quad a_y = 3\frac{m}{s^2} \quad v_y = 3\frac{m}{s}$$

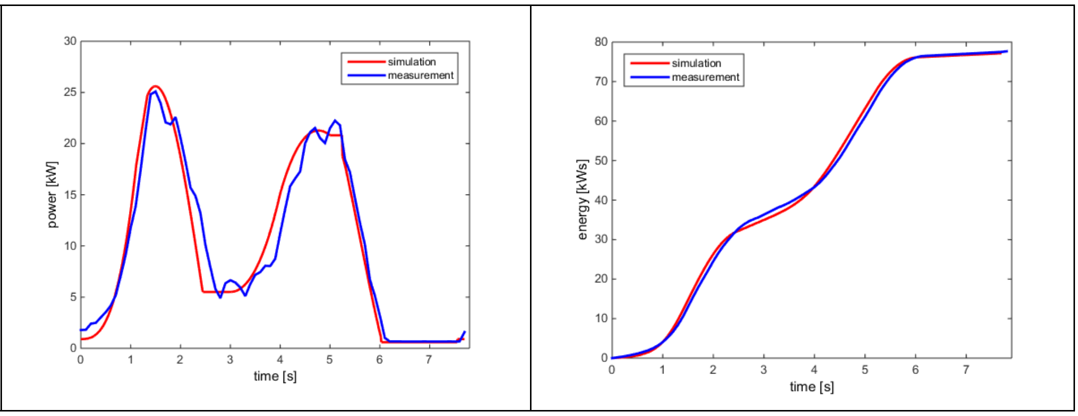


Figure 2. Matching simulation results with measured values

4 DEDUCING A META-MODEL

With this parameterized simulation model the energy demand for certain commands can be calculated very precisely. But because of long computation times, simulation models are rather inexpedient for fast analysis of various configurations. This is also true for the calculation of the mean energy demand for a complete storage rack served by a stacker crane especially with an intermediate circuit.

In order to solve this problem, appropriate meta-models will be introduced providing results with adequate precision demanding significantly less calculation time. By means of a physical simulation model a large data base is created, that can be used to develop the meta-model.

The dependent variable is the mean energy demand per double cycle of stacker cranes in AS/RS. For calculating the exact value of the mean energy demand for a certain configuration it is necessary to simulate each possible cycle. In a common warehouse more than a million double cycles need to be simulated for each configuration. Hence the calculation of the exact mean value is not possible at reasonable expense statistical methods are applied. Instead of simulating all possible cycles, a random sample of a sufficient size is taken and the mean value of the random sample is assumed to be the exact mean value of the whole population. In order to avoid significant deviation, a sufficient sample size has to be determined. For this purpose the frequency distribution of the energy demand per cycle for a chosen example with 1600 storage locations and 500 double cycles is considered in figure 3.

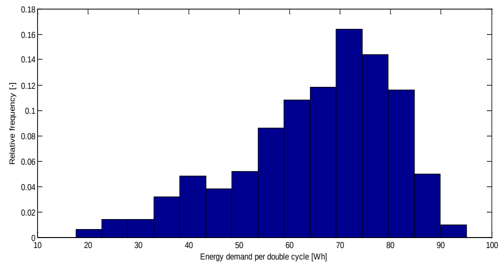


Figure 3. Relative frequency distribution of the energy demand per double cycle for a chosen example with random storage assignment

Obviously, figure 3 does not follow a Gaussian normal distribution. This can also be confirmed using statistical tests such as the Anderson-Darling-test [SBG12], which clearly rejects the null hypothesis of a normal distribution. When dealing with an unknown distribution the confidence interval I_K, based on the central limit theorem for big random sample size n > 30, is: [Rüs14]

$$I_K = \left[\bar{x} - z_{\left(1-\frac{\alpha}{2}\right)}\frac{s}{\sqrt{n}}; \bar{x} + z_{\left(1-\frac{\alpha}{2}\right)}\frac{s}{\sqrt{n}}\right]$$

Where:

$\bar{x}$ mean value of the sample

$z_{\left(1-\frac{\alpha}{2}\right)}$ (1−α/2)-quantile of the standard normal distribution

s the standard deviation of the sample

A sample of sufficient size promises acceptably small deviation of the estimate of a mean value. This is illustrated by figure 4, where energy demand per double cycle (blue), mean value (black) and the confidence interval (red and green) is recorded.

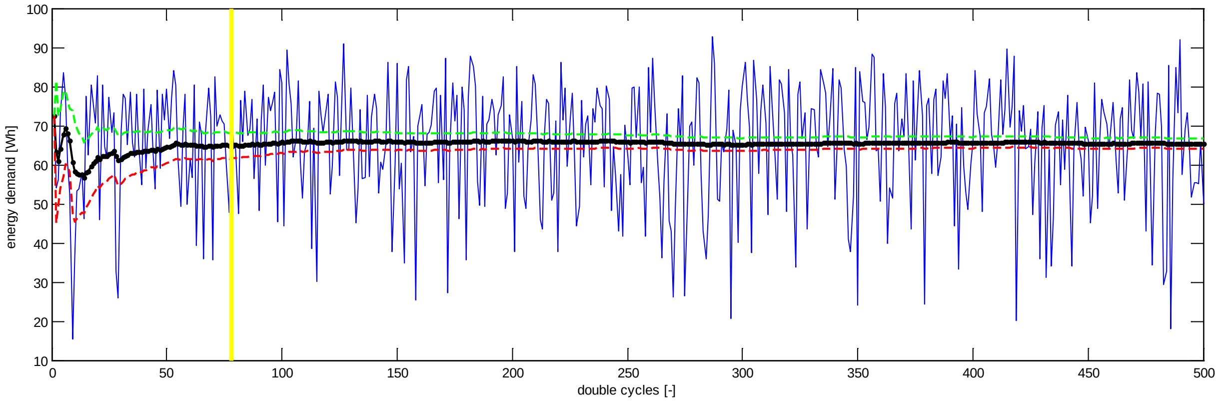


Figure 4. Energy demand per cycle for 500 double cycles for the chosen example with random storage assignment

In figure 4 the confidence interval is already less than +/- 5 % of the random sample mean value at a random size of 78 on a confidence level of 95 %. For further consideration double cycles are run till confidence interval is less than +/- 5 % or smaller than 2.5 Wh on a confidence level of 95 % 5 times in a row. So sample size is adapted automatically to each simulation.

After specifying the determination of the mean energy demand for a particular configuration, the data basis has to be created. The data basis is elaborated by means of statistical design of experiments. Suitable experimental designs for computer experiments can be created with latin hypercube design (LHD) [SBH10]. By means of LHD an experimental design with 1000 configurations is established. For each configuration the estimated mean value of the energy demand is calculated using the simulation model by simulating an individually adapted number of double cycles for each configuration.

When the data basis with 1000 configurations (quantity of experiments p) is available, the next step is to develop a meta-model. A well known method of multivariate data analysis is linear multiple regression which will be used in this context. A linear relation is assumed between the influencing factors (quantity of factors n) and the dependent variable (the mean energy demand $\boldsymbol{e}$) [Bac08].

$$\boldsymbol{e} = \boldsymbol{X} \cdot \boldsymbol{b} + \boldsymbol{\varepsilon}$$

Where:

$$\boldsymbol{e} = \begin{pmatrix} E_1 \\ \vdots \\ E_p \end{pmatrix}$$ vector of mean energy demands

$$\boldsymbol{X} = \begin{pmatrix} 1 & x_{11} & \cdots & x_{1p} \\ \vdots & x_{21} & \cdots & x_{2p} \\ 1 & \vdots & \ddots & \vdots \\ 1 & x_{n1} & \dots & x_{np} \end{pmatrix}$$

matrix of influencing factors $\boldsymbol{x}$

$$\boldsymbol{b} = \begin{pmatrix} b_0 \\ \vdots \\ b_p \end{pmatrix}$$ vector of regression coefficients

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_0 \\ \vdots \\ \varepsilon_p \end{pmatrix}$$ vector of unexplained deviations

$\boldsymbol{\varepsilon}$ is the unexplained deviation between the regression model and the simulation. The regression coefficients $\boldsymbol{b}$ are determined by means of the least squares method. The considered influencing factors $\boldsymbol{x}$ are listed with range of values and unit in table 2.

*Table 2. Influencing factors **x** with range of values and unit*

Influencing factor	Label	description	unit	Range of values
$\boldsymbol{x_1}$	l	Length of the automated storage and retrieval system	$[m]$	25-75
$\boldsymbol{x_2}$	h	height of the automated storage and retrieval system (measured from lowest level)	$[m]$	5-15
$\boldsymbol{x_3}$	m_R	Mass of the stacker crane minus weight of tower, lifting device and	$[kg]$	1000-2000

		live load		
x_4	m_M	Weight per meter of the mast	$[kg]$	20-50
x_5	m_H	Mass of the lifting device	$[kg]$	200-400
x_6	m_N	Live load	$[kg]$	20-100
x_7	r_x	Jerk of the horizontal drive	$[\frac{m}{s^3}]$	2-5
x_8	a_x	Maximal acceleration of the horizontal drive	$[\frac{m}{s^2}]$	2-5
x_9	v_x	Maximal velocity of the horizontal drive	$[\frac{m}{s}]$	3-6
x_{10}	r_y	Jerk of the vertical drive	$[\frac{m}{s^3}]$	2-4
x_{11}	a_y	Maximal acceleration of the vertical drive	$[\frac{m}{s^2}]$	2-4
x_{12}	v_y	Maximal velocity of the vertical drive	$[\frac{m}{s}]$	2-4
x_{13}	f_x	Coefficient of friction of the horizontal drive	$[-]$	0.01-0.10
x_{14}	η_x	Overall efficiency of the horizontal drive	$[-]$	0.7-0.9
x_{15}	f_y	Coefficient of friction of the vertical drive (converted with reference to weight force instead of normal force)	$[-]$	0.03-0.30
x_{16}	η_y	Overall efficiency of the vertical drive	$[-]$	0.7-0.9
x_{17}	η_{ZW}	Efficiency of energy exchange in intermediate circuit	$[-]$	0.85-0.98
x_{18}	p_0	Base load consumption	$[kW]$	0.500-1.25
x_{19}	e_{EA}	Mean energy demand during storage operation by the load handling device	$[Wh]$	0.52-3.25
x_{20}	J_x	Total moment of inertia of the horizontal drive referred to the engine	$[kgm^2]$	0.01-0.03
x_{21}	J_y	Total moment of inertia of the vertical drive referred to the engine	$[kgm^2]$	0.0005-0.001
x_{22}	d_x	Diameter of the driven gear (horizontal drive)	$[m]$	0.20-0.40
x_{23}	i_x	Gear ratio of the horizontal drive	$[-]$	7.5-15
x_{24}	d_y	Diameter of the driven gear (horizontal drive)	$[m]$	0.10-0.25
x_{25}	i_y	Gear ratio of the horizontal drive	$[-]$	7.5-15

Assumptions for the developed meta-model are as follows:

- Single-depth storage
- Random storage assignment
- Transfer point at the end of the aisle on lowest level

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

- Double cycle strategy
- Drive configuration with intermediate circuit connection

The model is developed with help of stepwise regression, in which the predictive variables are carried out by an automatic procedure. Interaction terms between the factors are also regarded. The meta-model offers the following advantages:

- Very fast and very easy calculation of the mean energy demand
- Quantification of the influence of every single factor
- Possibility for universal statements (in consideration of the assumptions)

5 RESULTS

The application of an automated stepwise linear regression analysis yields a linear approximation equation which takes the determined influencing factors into account and links them with the dependent variable. It is obvious to assume that there are interaction effects between certain influencing factors. For example the quantitative impact on the mean energy demand of reducing the mass per meter of the tower is also dependent on height and length of the warehouse. So interaction terms are considered as well.

For the presented investigation, the regression equation for the mean energy demand $\bar{E}$ is as follows:

$$\begin{aligned}\bar{E}[Wh] = -2.76 \cdot 10^{1} + 1.92 \cdot 10^{-1} \cdot l + 5.00 \cdot 10^{-1} \cdot h \\ + 3.45 \cdot 10^{-2} \cdot m_H + 2.57 \cdot 10^{-2} \cdot m_N \\ + 7.70 \cdot 10^{-1} \cdot r_x + 5.19 \cdot 10^{-1} \cdot a_x \\ + 4.39 \cdot 10^{1} \cdot f_y + 9.49 \cdot \eta_y - 1.17 \\ \cdot 10^{1} \cdot \eta_{ZW} + 6.00 \cdot p_0 + 3.90 \cdot e_{EA} \\ + 3.09 \cdot 10^{-4} \cdot l \cdot m_R + 1.85 \cdot 10^{-2} \cdot h \\ \cdot m_M + 3.73 \cdot 10^{-2} \cdot l \cdot v_x + 2.23 \\ \cdot 10^{-3} \cdot m_R \cdot v_x + 9.37 \cdot l \cdot f_x + 2.13 \\ \cdot 10^{-1} \cdot m_R \cdot f_x - 1.68 \cdot 10^{1} \cdot v_x \cdot f_x \\ - 8.19 \cdot 10^{-1} \cdot l \cdot \eta_x - 2.32 \cdot 10^{-2} \\ \cdot m_R \cdot \eta_x - 3.75 \cdot 10^{2} \cdot f_x \cdot \eta_x\end{aligned}$$

With a coefficient of determination R² of 0,988 the regression model is of very good quality. A coefficient of determination of 1 signifies a perfect mapping of the simulation data by the regression model. The standard error is 1.97 Wh. Further statistical parameters of the model are constituted in table 3.

Table 3. Statistics for the coefficients of the model

Coefficients	Estimation	Standard error	t-Statistics	p-value
constant	-2.76E+01	3.58E+00	-7.72	2.86E-14
x1	1.92E-01	6.84E-02	2.81	5.04E-03
x2	5.00E-01	3.30E-02	15.15	1.03E-46
x5	3.45E-02	1.09E-03	31.58	1.83E-151
x6	2.57E-02	2.72E-03	9.43	2.88E-20
x7	7.70E-01	7.23E-02	10.66	3.52E-25
x8	5.19E-01	7.30E-02	7.11	2.20E-12
x14	4.39E+01	4.52E+00	9.71	2.49E-21
x15	9.49E+00	8.07E-01	11.76	5.74E-30
x16	-1.17E+01	1.09E+00	-10.74	1.71E-25
x18	6.00E+00	3.18E-01	18.85	7.26E-68
x19	3.90E+00	1.40E-01	27.90	1.82E-126
x1*x3	3.09E-04	1.44E-05	21.42	9.50E-84
x2*x4	1.85E-02	7.21E-04	25.61	3.93E-111
x1*x9	3.73E-02	4.32E-03	8.64	2.28E-17
x3*x9	2.23E-03	1.57E-04	14.22	7.36E-42
x1*x13	9.37E+00	1.59E-01	58.95	0
x3*x13	2.13E-01	7.85E-03	27.15	2.02E-121
x9*x13	-1.68E+01	2.53E+00	-6.65	4.73E-11
x1*x14	-8.19E-01	7.55E-02	-10.85	5.86E-26
x3*x14	-2.32E-02	1.35E-03	-17.13	9.48E-58
x13*x14	-3.75E+02	2.09E+01	-17.91	2.87E-62

To check the validity of the regression model, a review of the assumptions of a regression analysis is presented. The review involves the following steps [Bac08]:

- Test for homoscedasticity
- Test for normally distributed residuals
- Test for no residual autocorrelation
- Check the mathematical expectation of the disturbance variable, which should be ideally 0
- Validating the regression model with help of another data basis.

Test for homoscedasticity: The Engle test for residual heteroscedasticity confirms the null hypothesis of no conditional heteroscedasticity (p-value 0.31). Figure 5 illustrates the residuals with ascending calculated energy demand. It is obvious that the datais not subjected to nay heteroscedasticity.

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

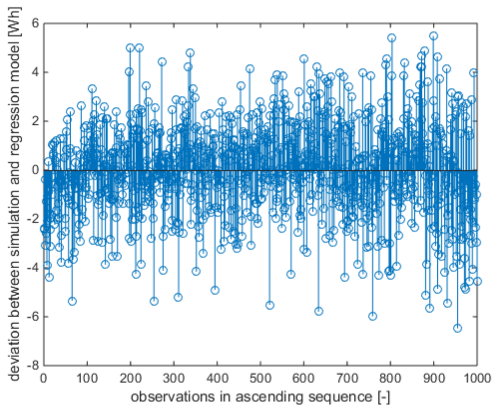


Figure 5. Residuals in ascending sequence of the energy demands

Test for normally distributed residuals: Figure 6 shows the relative frequency distribution of the residuals which is rather similar to a normal distribution.

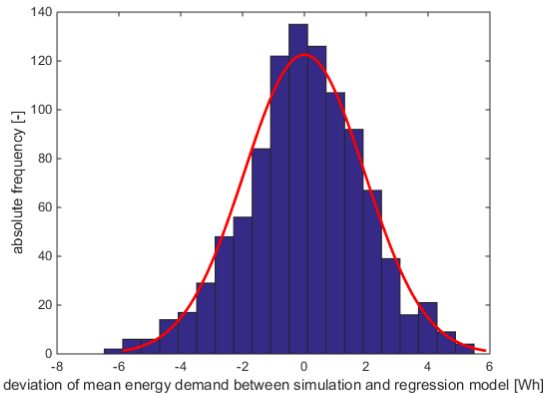


Figure 6. Absolute frequency distribution of the residuals

Test for no residual autocorrelation: The Ljung-Box Q-test confirms the null hypothesis of no autocorrelation (p-value 0.25).

The mathematical expectation of the disturbance variable should be ideally 0: The mean value of the residuals is in this case 1.12e-14.

Consequently the assumptions for a regression model are fulfilled. Next the model should be tested on another data basis. The data basis for the test is also created by LHD-design and contains 5000 new configuration with influence factors in the range of values stated in table 1. Figure 7 shows as a result the percentage deviation between simulation data and the regression model (red: test data, blue: fitting data).

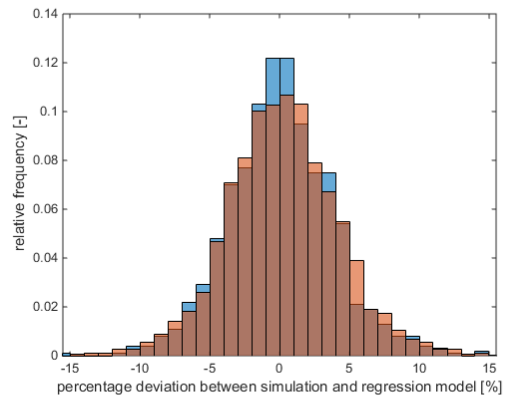


Figure 7. Relative frequency distribution of the percentage deviation for the test data base

The regression model is valid for the test data base with a maximum percentage deviation of 15 % for a few extreme cases. For 98.4 % of the simulated configurations the regression approximation deviates only by a maximum rate of 10 %. Thus, by use of this meta-model the mean energy demand can be approximated quite well.

6 Conclusion

In this paper a method is presented for quick calculation of the mean energy demand of storage and retrieval systems utilizing stacker cranes with intermediate circuit connection. Conditions with regard to the exchange of recoverable energy between the main drives of such stacker cranes vary with each cycle. So till now analytical approaches to calculate the mean energy demand of systems with this drive configuration are not available and will hardly be successful.

Within the presented method a meta-model for approximation of the mean energy demand of stacker cranes in small part stores is developed, using multivariate data analysis based on results of a simulation model.

The meta-model is distinguished by the fact that no time consuming simulation experiments are necessary to determine the key figure for energy demand. Calculation can now be performed very fast and easily without any simulation tools. In addition the impact of influencing factors can be quantified.

In consequence the application of the meta-model facilitates the consideration of energy consumption of such systems for planners and operators essentially.

Literature

[EG12] Ertl, R.; Günthner, W. A.; Fischer G.: Energieeffiziente Intralogistik auf Geräteebene am Beispiel des Regalbediengeräts. Tagungsband Magdeburger Logistiktage, S. 65 ff., Fraunhofer Verlag 2012

[FL11] Furmans, K.; Linsel, P.: Leichtbau bei Unstetigförderern durch Einsatz moderner Werkstoffe. Tagungsband 7. WGTL-Kolloquium, S. 14-25, Verlag Praxiswissen Service, Rostock

[Wah12] Wahle, A: Leichtbau für AKL-Geräte – Perspektive Faserverbundwerkstoffe?. 21. Deutscher Materialfluss-Kongress, VDI-Bericht. Düsseldorf. 2012

[Wah14] Wahle, A: Spann einfach den Bogen. Hebezeuge Fördermittel. 9/2014. S.504-506. Huss Verlag.

[EG13a] Ertl, R.; Günthner, W. A.: Energieeffiziente Bahnplanung von Regalbediengeräten – Zwischenkreis ermöglicht einen niedrigen Gesamtverbrauch. Hebezeuge Fördermittel 1-2/2013, S. 26-29, Huss Verlag

[Sch14] Schulz, R.: Untersuchung und Ableitung geeigneter Lagerbetriebsstrategien zur Verringerung des Energiebedarfs von Regalbediengeräten. 2014. Otto-von-Guericke-Universität Magdeburg

[Som14] Sommer, T.: Die energieeffiziente Lagerplatz-Zuordnung in aHRL. Hebezeuge Fördermittel. 10/2014. S.586-588. Huss Verlag.

[MM14] Meneghetti, A.; Monti, L.: Multiple-weight unit load storage assignment strategies for energy-efficient automated warehouses. International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management. Volume 17. Issue 4. 2014

[GSEH11] Günthner, W. A., Schipplick, M., Ertl, R.; Hahn-Woernle, P.: Wettbewerbsfaktor Energieeffizienz – Simulationsmodell für Entwicklung und Betrieb von automatischen Regalbediengeräten. F+H Fördern und Heben 6/2011. S. 276-279. F+H Fördern und Heben 7-8/2011. S. 326-329. Vereinigte Fachverlage

[BLSF12] Braun, M.; Linsel, P.; Schönung, F.; Furmans, K.: Energiebetrachtung im Lager- und Kommissioniervorgang. . Tagungsband 8. WGTL-Kolloquium. S. 110-116. Otto-von-Guericke-Universität Magdeburg. Magdeburg

[SSTSZ13] Siegel, A.; Schulz, R.; Turek, K.; Schmidt, T.; Zadek, H.: Modellierung des Energiebedarfs von Regalbediengeräten und verschiedener Lagerbetriebsstrategien zur Reduzierung des Energiebedarfs. Tagungsband 9. WGTL-Kolloquium. S. 91-108. Verlag Praxiswissen Service. Dortmund

[MM13] Meneghetti, A.; Monti, L.: Sustainable storage assignment and dwell-point policies for automated storage and retrieval systems. Production Planning & Control: The Management of Operations. Volume 24, Issue 6, 2013

[EG13b] Ertl, Rainer; Günthner, Willibald A.: Schnell zu aussagekräftigen Werten gelangen. F+H Fördern und Heben 6/2013. S. 12-14. F+H Fördern und Heben 7-8/2013. S. 12-15. Vereinigte Fachverlage

[HEG13] Habenicht, S.; Ertl, R.; Günthner, W. A.: Analytische Energiebedarfsermittlung von Intralogistiksystemen in der Planungsphase. Tagungsband 9. WGTL-Kolloquium. S. 77-90. Verlag Praxiswissen Service. Dortmund

[LER14] Lerher, T.; Edl, M.; Rosi, B.: Energy efficiency model for the mini-load automated storage and retrieval systems. The International Journal of Advanced Manufacturing Technology. Volume 70. S. 97–115. 2014

[SBG12] Specht, K.; Bulander, R.; Gohout, W.: Statistik für Wirtschaft und Technik. Oldenbourg. München. 2012

[Rüs14] Rüschendorf, L.: Mathematische Statistik. Springer Verlag. Berlin. 2014

[SBH10] Siebertz, K., van Bebber, D., Hochkirchen, T.: Statistische Versuchsplanung – Design of Experiments (DoE). Springer Verlag. Heidelberg. 2010

[Bac08] Backhaus, K.: Multivariate Analysemethoden – eine anwendungsorientierte Analysemethoden. Springer Verlag. Berlin. 2008

DOI: 10.2195/lj_NotRev_ertl_en_201602_01
URN: urn:nbn:de:0009-14-43242

Dipl.-Ing. Rainer Ertl, Research Assistant at the Chair for Materials Handling, Material Flow, Logistics, Technische Universität München.

Prof. Dr.-Ing. Dipl.-Wi.-Ing. Willibald A. Günthner, chairholder of the Chair of Materials Handling, Material Flow, Logistics, Technische Universität München.

Address: Lehrstuhl für Fördertechnik Materialfluss Logistik, Technische Universität München, Boltzmannstraße 15, 85748 Garching, Germany,
Phone: +49 (89) 289-15921, Fax: +49 (89) 289-15922,
E-Mail: kontakt@fml.mw.tum.de