Quantitative Performance Parameters for Industrial Bin Picking Applications

Matthias Sarna, Jens Weist
Volkswagen AG,
Wolfsburg, Germany
E-Mail: [first.last]@volkswagen.de

Kristof Meixner
TU Wien,
Vienna, Austria
E-Mail: [first.last]@tuwien.ac.at

Arndt Lüder
Otto-von-Guericke University Magdeburg, Germany
and CDP, Vienna, Austria
E-Mail: [first.last]@ovgu.de

***Abstract*—Industrial Bin Picking (IBP) is a central automation object in factory automation plants. Even with several successful research activities in the field of designing Industrial Bin Picking Applications (IBPAs), many known applications are thereby still not industry ready caused by insufficient technical availability. Performance metrics for different kinds of applications and devices are state of the art, however not for the complex engineering domain of IBPAs. In this paper we introduce and define Quantitative Performance Parameters (QPPs) for all engineering phases of IBPAs. Those QPPs are measurable values used as performance indicators. This allows lean engineering by measuring objectively industrial performance, especially already mentioned technical availability of IBPAs. Furthermore, those QPPs indicate objectively optimization approaches and leads towards industry ready IBPAs.**

***Index Terms*—Industrial Bin Picking, Factory Automation Systems, Performance Parameters, Lean Engineering**

I. INTRODUCTION

IBP is one central automation object in factory automation plants [1]. These IBPAs aim to automate the supply of not ordered workpieces into production processes. Thereby the application layout and functionalities depend on process requirements, which are derived from workpiece properties, robot size and kinematic, required effector technology and not least vision device functionalities. As it is a multidisciplinary task, experts from different domains as robotic, process, production and computer vision are involved.

Thus, IBP is an individual case from the engineering point of view. This individuality leads to challenging engineering in all phases [2], [3]. The explained individuality is the reason for a hard to establish and currently not existing ready-to-use bin picking standard concept or application for all or a certain use case. This demands a sophisticated engineering process for each IBPA.

In our analysis of until now 69 IBP implementations in different industrial branches we figured out, that a significant number of IBP projects suffer from complexity, huge engineering effort, exceeding cost and the lack of a required high technical availability. Several IBPAs failed in production and were rated as not industry ready. These are general reasons why IBP is still not state of the art in industrial factory automation systems.

In this paper we enlarge the bin picking task from intelligent *workpiece recognition and picking* up to the whole for industrial workpiece supply required sequence with IBP. As we found out in our analysis, not only vision technology and AI approaches but also the whole application layout and the concept have important influence on the success of IBP.

For this paper we address the following research question: *Which quantitative properties are capable to describe precisely the performance of Industrial Bin Picking Applications (IBPAs) in all project phases and preliminary define the application performance?* Our own goal is a generic approach for industrial sustainable bin picking applications covering the whole necessary sequence from delivery in a container until successful handover and therewith ordered workpiece supply into industrial factory automation systems.

Therefore we analyze and categorize possible failure and error situations, expand existing methods and introduce new technical availability related performance parameters. With this method we aim QPP which are applicable and continuous in all engineering phases.

Related work we present in this paper in Section II. In Section III the industrial use case is followed by the central research question. The new QPP for IBPAs we introduce in Section IV. For evaluation in Section V we compare required and actual QPPs values. Section VI concludes this paper and points out a research agenda for future work.

II. RELATED WORK AND STATE OF TECHNOLOGY

In general total application cost is a central and measurable criterion so far the application is comparable regarding quality and performance. Especially for IBPAs performance and quality parameters are still not defined. This section introduces state of technology of three already known parameters:

1) VDI 2860 Handling Technology: IBPAs aim an ordered supply of previous not ordered workpieces. Thereby the Order Condition (OC) gives information about known and unknown orientation and position coordinates. An ordered workpiece condition with three known rotational and three translational coordinates can be written as OC (3 ; 3). A not ordered piece, respectively with an unknown OC equals OC (0 ; 0) [4].

2) Technical Availability: Technical availability is, according to VDI 3423, the percentage of occupied time in which a application is available for production without any technical errors [5]. Availability is the main performance value for all industrial factory automation systems.

TABLE I
INDUSTRIAL BIN PICKING CASES C0 - C3 IN IBPAS

loading case	unloading case	case C
load failed	no unload	**C0**
all OC	not intended into container	**C1**$_a$
	not intended on container	**C1**$_b$
	not intended in application cell	**C1**$_c$
	not intended on handover station	**C1**$_d$
	not intended stacked in effector	**C1**$_e$
	not intended loss of not intended loaded workpiece	**C1**$_f$
all OC	intended unload from effector - intermediate step	**C2**$_a$
	intended unload from effector - deviation detected while handling	**C2**$_b$
	intended unload from device - deviation detected at device	**C2**$_c$
	intended unload caused by more / less parts detected than intended / expected	**C2**$_d$
OC $\neq$ (3 ; 3)	unload OC (3 ; 3)	**C3**$_a$
OC (3 ; 3)	unload OC (3 ; 3)	**C3**$_b$

3) Cycle Time and Throughput: Cycle time [6] and throughput [7] are established as universal parameters among others for factory automation systems. As those are application and layout related in IBPAs, they are suitable as QPPs.

This section summarizes known approaches towards QPP. As those and other known concepts are general and not specific enough for IBP [8] and complex engineering of IBPAs needs to be managed, we illustrate in the following section a generic IBP use case to build up on that QPPs for IBP in Section IV.

III. INDUSTRIAL BIN PICKING USE CASE

This section aims to describe a generic but industrial requirements related IBP use case. The generic approach is necessary since state of technology does not know established IBP standard or core concept neither component.

According to known Industrial Bin Picking (IBP) definitions, [1], [9], [10] we focus automated and defined workpiece supply out of standard container of previous not ordered workpieces into it's following manufacturing process. This excludes common bin picking or laboratory use cases.

To assure a generic approach we replace technology related terms such as gripping or picking by **loading** and placing and releasing by **unloading** in functional context.

In the IBP use case a certain workpiece is transformed throughout the process from OC (0 ; 0) to OC (3 ; 3). Table I shows four as possible identified cases (C0 - C3) in IBP. Each line is the combination of a certain loading (first column) and unloading situation (second column) leading to it's specific case (third column).

It is important to defined that a successful supply finishes in case C3. Therefore cases C0, C1 and C2 are considered as non productive and require a supply process restart.

Use case relevant resources are in an IBPA included devices such as standard container, a handling device with effector, handling supporting devices (e.g. for adjustment or turning), handover device (respectively buffer storage) and for common concepts computer vision systems.

In C1 cases not detected issues occure and thus not intended unloads result. This may increase cycle time t_{cycle} and additionally cause process errors or even mechanical damage by not intended unloaded parts. To attend an occurring error operator action is necessary.

Despite initial known or applicable OC, cases C2 describe an intended unload to avoid errors respectively mechanical damages. Cases C2 increase t_{cycle} but cause no process errors as long following process do not suffer from not supplied parts.

Supplying workpieces in cases C3 mean a successful supply with OC (3 ; 3). As a special use case according to Sarna et al. [1] blind loading concepts are realized in industrial environment as a sequence of at least $C2_a$ and $C3_b$.

A. Research Question

The previous sections show lack of specific and quantitative rating criteria for IBPAs. This leads repeatedly to ambiguity about project and process requirements and missing measurability of performance aspects. As a consequence several bin picking concepts and applications were rated as not industry ready. Since there are beside standard coefficients no established values or parameters to cover the performance with numerical values for IBPAs, we point out the following research question: *Which quantitative properties are capable to describe precisely the performance of Industrial Bin Picking Applications (IBPAs) in all project phases and preliminary define the application performance?* Project phases including feasibility studies, acceptance tests and long term performance monitoring in production. For this we created a data entry sheet with 186 technical and economical details for quantitative and qualitative data. Resulting QPPs are introduced in Section IV.

IV. QUANTITATIVE PERFORMANCE PARAMETERS

For this and earlier work we analyzed IBP approaches, projects and applications by structured data collection expecting qualitative and quantitative data. In this section we summarize our empiric determined Quantitative Performance Parameters (QPPs) for Industrial Bin Picking Applications (IBPAs). Finally we examine different conditions and limits with new QPPs for IBPAs. Each QPP is listed in Tab. II by name, equation, industrial required value (Req.) and actual average value of our analysis.

A. Emptying Rate τ

Both, human operators and IBPAs, aim to empty completely delivered and therewith planned workpieces and further to supply into the manufacturing process. For mathematical description of this emptying process we introduce variables for:

- the initial amount of workpieces in a container i_a
- the currently remaining workpieces in the container i_e
- the successfully removed workpieces from a container j

It follows the relation in equ. 1.

$$i_a = i_e + j \tag{1}$$

As operators are able to supply all delivered workpieces, a central criterion for IBPAs is the emptying rate τ of delivered

TABLE II
INDUSTRIAL REQUIRED QPP FOR IBPAS

Parameter		Req.	Actual
Emptying Rate	$\tau = \frac{j}{i_a}$ (2)	1	0.8
Pose Rate	$\xi = \frac{1}{\beta}$ (3)	1	0.0625
Picking Rate	$\eta = \frac{n}{j_c}$ (4)	1	0.3 - 1
Total Picking Rate	$\theta = \frac{\sum_{c=1}^{n} \eta_c}{i_a}$ (5)	1	0.73
Production Output	$T_{cycle} = \frac{t_r}{t_{cycle}}$ (6)	1.5*	0.6 - 1.1
Total Production Output	$T = \overline{T_{cycle}}$ (7)	1.5*	1.03
Technical Availability	$V_{TS} = (1 - \frac{t_{down}}{t_{occupied}})$ (8)	1	0.6 - 0.95
Loading Parameter	$\sigma = \frac{\kappa}{\gamma}$ (9)	1	0.6
Total Loading Parameter	$\Sigma = \frac{\kappa}{\psi}$ (10)	≥ 0	-
Optimization Indicator	$\zeta = \gamma - \kappa$ (11)	0	4.3

workpieces [11]. τ is for IBPAs in engineering phase just experimental ascertainable. In case of $\tau = 1$ no workpieces remain in the container after the bin picking process. This fulfills a central industrial requirement. For the case $\tau \neq 1$ an error occurs since an operator needs to remove the remaining workpieces manually.

For this paper we analyzed main influences on τ as amount of load poses β, emptying strategy, reachability in relation to container shape and adaption quality between workpiece, robot, effector and vision device. Further β is also a QPP for IBPAs since it points at the effectiveness of applied load poses under consideration of the whole application.

Additional we introduce the pose parameter ξ as QPP as reciprocal of number of load poses per workpiece β. As many load poses mean commissioning effort and an error source by any changes made after wards. ξ is a central QPP since $\xi = 1$ with $\tau = 1$ and $\beta = 1$ could mean, globular workpieces, certain prepared OC or other special conditions. These three cases are excluded by the interpretation of the Industrial Bin Picking (IBP) use case in Section III.

B. *Picking Rate η and θ*

The picking rate η is an **effectiveness** parameter of successful loaded parts j_c (for one-workpiece effector maximum $j_c = 1$, two-workpiece effector maximum $j_c = 2$ etc.) per try, see Tab. II. And with n the number of tries until a successful handover, including the events C0 to C3 in tab. I. With the parameter ω as individual application based limit value for acceptable tries for a successful handover before an error.

A best possible emptying series, consisting only of $C3$, equals $\eta = 1$ and $\tau = 1$. In case of $n = \omega$, a series of cases C0, C1 or C2 no workpieces were successful supplied and the sequence ends with an error, see Tab. III. In this case η is rated with $\eta = 1 + n$ respectively $\eta = 1 + \omega$.

TABLE III
PICKING RATE η FOR SINGLE EFFECTOR

n	1	2	3	...	n	ω
j$_c$	1	1	1	1	1	0
η	1	2	3	...	n	n + 1

η is related to j_c a single row parameter, while total picking rate θ faces the averaged picking rate on the initial amount of workpieces in a container i_a.

In case of a high quality IBPA which means only $C3$ cases according to Tab. I and therewith total successful picking series, follows $\theta = 1$.

C. *Vision Parameters*

For computer vision based IBPAs it is necessary to define the detection and loading performance. In this in the bin visible workpieces ψ, in the bin identified workpieces γ and from the bin loadable workpieces κ take place.

As relation of loadable workpieces κ to identified workpieces γ the loading parameter σ is a central performance parameter. A totally flexible engineered IBPA, which is capable to load all identified workpieces, is characterized by $\sigma = 1$. On the other hand in case of $\sigma \neq 1$, not all detected workpieces are loadable, with a probable consequence of a not complete emptied bin with $\tau \neq 1$.

The relation of in the bin visible workpieces ψ to in the bin loadable workpieces κ is the total loading parameter Σ, which rates the detection and loading performance of a IBPA.

In case of a constant value of $\sigma = 1$ and $\tau = 1$ the IBPA is completely optimized from computer vision point of view. Since this is an industrial requirement but most IBPAs does not reach this performance level, we introduce the optimization indicator ζ as subtraction of in the bin identified workpieces γ from in the bin loadable workpieces κ.

In case of $\zeta \neq 0$, the application has potential to be optimized. Further we analyzed two possibilities for $\zeta \neq 0$. There are collision related ζ_c and missing load pose related ζ_p. Both can be automatically pointed out and indicate clear optimization needs. In case of $\sigma = 1$ and $\zeta = 0$ but also $(\kappa; \gamma) = 0$ and $i_e > 0$ the computer vision resource needs optimization.

TABLE IV
PRODUCTION OUTPUT CASES

possible cases	Total Production Output	situation
C0; C1; C2	0	error, no supply
C0; C1; C2 $>$ C3	$0 < \mathrm{T} < 1$	UP
C3 $>$ C0; C1; C2	1	set operation
C3 $>>$ C0; C1; C2	$1 < \mathrm{T} < \mathrm{T}_{max}$	OP
C3	$\mathrm{T}_{max}\ with\ \mathrm{t}_{cycle-min}$	OP$_{max}$

D. t_{cycle} and throughput

Cycle time t_{cycle} is known as time in which an unit of measure is completed so that the application provides the target output [6]. Therefore it is necessary to define an unique recurring event for one cycle. Since the set of required workpieces can vary and adjusting, turning and initial loading position may vary, exclusively the delivery at the handover device is a suitable and recurring event in IBP.

To fulfill the IBP requirements we mention Over Performance (OP) as it is the necessary throughput to tolerate beside the aimed case C3 not productive cases C0, C1 and C2, respectively Under Performance (UP) to describe lack of production output. Therefore we define the production output as T_{cycle} as relation of required cycle time t_r and finally realized t_{cycle} in one cycle. Averaged T_{cycle} over a period of interest, is total production output T. Tab. IV shows in each line possible ranges for T with related cases, a reference of T and the situation as consequence in the columns.

With realizable OP with stable IBP processes based on $C3$, $T_{cycle} \geq 1$, $(\tau;\eta;\sigma) = 1$, decoupling of the supplying IBPA and the supplied following process using buffers is possible. Therewith planing of throughput variability is possible to avoid down time errors. Remembering that assuring availability and thereby avoiding errors is one central industrial requirement. Based on the inaccuracy propagation in our future work, we can estimate*, see tab. II, the probability of cases C0, C1 and C2 and so the number of required buffer spots respectively the required T_{cycle}, T and OP.

V. EVALUATION

For this paper we analyzed in total 69 IBPAs and 18 developed and used within the Volkswagen trust in all engineering related project phases. We were able to use the named QPPs in all IBPAs resulting in a complete set of parameters for further use in quality management.

Table II summarizes in this paper introduced QPPs, point out industrial aimed respectively required values and average of actual performance of analyzed IBPAs. All parameters are without units but could be displayed in percent.

The summarized evaluation in Tab. II shows a gap between industrial required and actual performance values. With these QPP we are able to point out and precisely name optimization needs for each application and for research in general.

VI. CONCLUSION AND RESEARCH AGENDA

This work aims to enable reliability, comparability and scalability in the engineering process of Industrial Bin Picking Applications (IBPAs) based on Quantitative Performance Parameters (QPPs) towards lean engineering in all phases. As shown, it is possible to precisely describe the IBP use case within categories and measurable parameters.

The integration of QPPs in the early planing and engineering phase reduces the risk of incorrect planning and improves the reliability of estimated performance values about the IBPA, as a detailed functional respectively skill based specification is possible. Further manufacturers and customers requirement specifications get resilient measurable. During commissioning a sustainable and focused optimization process is guaranteed. Finally the production phase asks for live and displayed QPPs.

With in this work presented QPPs for IBPAs it is feasible to analyze and rate IBP use cases in an objective and systematic procedure. Therefore we pointed out limits and meanings of these new engineering parameters. Our QPPs for IBPAs are applicable for error lists, production monitoring, data analysis, evaluation of current needs for action in all project phases.

In our future work we concentrate on an engineering method for IBPAs, which involves detailed requirements and QPPs to derive the necessary throughput. A necessary capability is a guideline for a systematic analysis of existing IBPAs and potential IBP use cases by using QPPs, since we examined the complexity related limitations of our QPPs network.

Additional we will research the resource related inaccuracy in IBP context to improve technical availability of IBPAs by avoiding cases C0, C1 and C2.

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