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Influence of Bottleneck on Productivity of Production Processes Controlled by Different Pull Control Mechanisms

Nataša Tošanović * and Nedeljko Štefanić

Department of Industrial Engineering, Faculty of Mechanical Engineering and Naval Architecture,
University of Zagreb, Ivana Lučića 5, 10 000 Zagreb, Croatia; nstefanic@fsb.hr
* Correspondence: ntosanovic@fsb.hr

Abstract: The goal of any lean implementation in production process is achieving better production performances and one of them is productivity. Among many lean principles, pull principle is the most complex to achieve. There are different production control mechanisms for achieving pull and making decision which one to apply can be demanding because sometimes it is not obvious which is the best for specific situation. Many different production parameters influence production process and for one production setting, one control mechanism is the best choice, but for another production setting it might not be. One goal of this study was to research the influence of bottleneck in the production process in regard to achieving better productivity by applying pull principle. Some of the literature considered deals with the topic of bottleneck and pull but focuses only on bottleneck or in addition on one another production parameter and most of the literature studies up to three different pull control mechanisms. One of the objectives of this study was also to fill the research gap in a way to investigate more mechanisms, particularly, according to the literature, those most widely used in various production conditions with emphasis on bottleneck. The advantage of this research is that in addition to the bottleneck, other parameters, namely the number of control cards, variations and processing time are considered. For that reason, simulation experimentation was conducted and as a result regression functions modelling the relationship between productivity and mentioned parameters for four different pull control mechanisms are gained. The analysis showed that the existence of a bottleneck affects the effectiveness of pull mechanisms in terms of productivity.

Keywords: lean manufacturing; production process; productivity; pull; production control; Kanban; Conwip; DBR; Hybrid Kanban/Conwip

1. Introduction

Digitalization and Industry 4.0. (I 4.0) are the latest trends in industry, specifically in managing and controlling production. However, evidently, well known methodologies for production management and improvement of production processes such as lean manufacturing, six sigma etc. are still important. Thus, authors [1] point that the only technological adoption which is characteristic of I 4.0 will not lead to distinguished results. Lean manufacturing practices help in the installation of organizational habits and mindsets that favor systemic process improvements, supporting the design and control of manufacturers' operations management towards the fourth industrial revolution [1]. In addition, it is known that changes toward Industry 4.0 could be significant and any mistakes or skipped step could cause waste in the future [2]. It is obvious how lean manufacturing is still an important topic, both for research and practice.

Womack, J.P. and Jones, D.T. define five basic lean principles:
- Value;
- Value chain;
- Flow;
- Pull;

- Perfection [3].

Pull principle is the most complex principle for the company to achieve, mainly because many preconditions need to be satisfied in order to start with implementing this principle. Pull emerged from one of the most known paradigms of Toyota Production System (TPS) and that is Just-in-Time. (JIT). The idea behind Just-in-Time is to deliver the product to the customer as close as possible to when the customer requires it. Hopp and Spearman state that the Kanban is misunderstood as a synonym for pull and JIT production, when Kanban is rather just one of the means for achieving pull thus, is itself a pull control mechanism [4]. Later other pull control mechanisms have emerged.

The aim of this study was to research the influence of bottleneck on productivity with respect to different pull control mechanisms, in different production conditions defined by level of variations, number of pull control cards and processing time. The influence of lean manufacturing implementation on productivity is well described in literature [5–9]. Adoption of lean manufacturing results in an increase of productivity not just in production processes, but also in the design of a product. Hence, in [10], the case study of adopting lean in product design is presented and it is described that after adopting TPS principles the number of design cases undertaken by the design department increased [10].

However, how do pull control mechanisms affect productivity and how do they behave depending on whether that there is or there is not bottleneck in the process? Karrer [11] argue that production control mechanisms have a direct influence on delivery, and that is driven by production lead time and by the productivity.

On the other hand, bottleneck detection in manufacturing is the key to improving production efficiency and stability in order to improve capacity and thus productivity.

In Chu ans Shih's work, [12], it is presented that some studies have found that simply increasing the number of Kanban cards (inventory level) cannot resolve bottleneck problems. Bonvik [13], researched three mechanisms Kanban, Conwip and Hybrid Kanban/Conwip in terms of bottleneck, but only how it affects the production lead time.

According to the relevant literature, the most widely used three control mechanisms are Kanban, Conwip and Hybrid Kanban/Conwip [14]. On the other hand, DBR mechanism was specially designed for processes with bottleneck [15]. There is a gap in research that might take into consideration multiple mechanisms in the context of the impact of bottlenecks on productivity. Therefore, the intention of this study was to answer the following research questions:

- Q1: Does the bottleneck affect the efficiency of the pull control mechanism (PCM)?
- Q2: Is the impact of the existence of a bottleneck on the efficacy of PCM different depending on the level of variability, processing time, as well as the level of work-in-process (defined by the number of PCM control cards in the process)?

1.1. Literature Review

1.1.1. Lean Manufacturing

Lean manufacturing is one of the major methodologies for production improvement and managing highly effective production processes. It has evolved from TPS. The interest for TPS in the western countries emerged after the success of the joint venture NUMMI of Toyota and General Motors, after which the book called The Future of Automobile was released. In a later book, The Machine that Changed the World, with the same focus of research, the book John Krafik uses the term *lean* for describing TPS for the first time [16,17]. Today Lean manufacturing is considered as production paradigm the goals of which are to produce value for the customer and to shorten the lead time of the production process [18,19]. The West adapted Japanese tools and principles to reduce waste, lead time and value for the customer. Thus, lean manufacturing in its early stage consisted of tools mainly for the shop floor. Later the paradigm of lean manufacturing or lean production evolved into the paradigm of lean thinking. This is why authors in [19] have made the distinction of lean thinking at the strategic level and lean thinking on the shop floor level, and they found that it is very important to understand lean on both levels,

as a whole, in order to apply the right tools to provide value for the customer. They state that understanding lean thinking as only shop- floor methodology leads to a limited understanding of what contemporary lean approaches are about. According to those authors lean thinking has evolved from a production toolkit, through single supplier-customer focus dyad, to a strategic value proposition [19]. Thus, lean manufacturing both as a production toolkit, as well as strategic philosophy can be implemented in other environments, not just in manufacturing.

1.1.2. Lean Application in Different Industries

Over the years lean has evolved both as a toolkit and strategy for application in many different industries and types of organization. For example, possibilities of implementing lean in public sector, as well as its specificity are described in [20]. That research presented a case study of lean implementation in the Brazilian regulatory agency and revealed two decisive aspects in public environment; human and legal. Many times, these kinds of initiatives are dealing with legal aspects which involves slow bureaucratic processes; thus, these initiatives have to be supported by awareness and support of more decision makers other than managers willing to improve processes [20]. An interesting case study was presented by Jing, S. et al. The authors developed procurement value stream mapping as a tool of improving procurement process in manufacturing warehouse [21]. They showed improvement by this method in reducing business inventories, shortening the plan-making cycle, billing cycle, information cycle, logistics cycle a procurement cycle. Another application of values stream mapping, but in retail sector was presented in case study by Yanfang Qin and Hongrui Liu [22]. The authors presented that the methodology could improve supply chain management efficiency and customer satisfaction. Of lean implementations in public sectors the implementation in healthcare is the best explored. Implementation of lean in healthcare is well described in paper [23]. Authors described the successful implementation of lean tools in a French public hospital which has improved the quality of health services delivered to the patient. Another case study of lean implementation in healthcare is presented in paper by Antosz et al. [24]. They showed successful application of Value stream mapping (VSM), one of the widely used lean tools. Another application of VSM in healthcare system is presented in work of Cardoso [25]. The case study is undertaken in emergency care. The goal was to show the utilization of VSM for detecting wastes and improvement points. The result of proposed improvements implementation was shorter lead time. An interesting research regarding lean implementation in healthcare, but in outpatient departments was carried out by Ting Yu, Kudret Demirli and Nadia Bhuiyan, [26]. They have developed the framework to guide Lean transformation and solve the issues in outpatient's department through identifying demand, coordinating resources, levelling schedules, and controlling wait times. Research [27] presented a literature review of implementation of lean in healthcare. The authors have reported the increase of papers dealing with lean in healthcare, however they found that the lack of continuous improvement throughout the whole organization exists, while most of the articles describe isolated implementation in different areas of organization. Thus, they suggested, there are more possibilities in spreading isolated initiatives on the whole organization and promotion of cultural changes in context of lean. As lean evolved as a philosophy, its application became wider. One example of the successful application of lean is in the pharmaceutical industry, especially in the laboratory as presented in the article [28], which showed the success of the use of lean in this area. The authors have found three types of waste; transport, waiting and defects to comprise almost 51.4% of the problem regarding lean assessment of the laboratory. Interesting case study, also in pharmaceutical industry was presented by Byrne et al [29]. The goal of the study was to reduce downtimes by applying Lean Six Sigma tools. The results of application of lean and six sigma tools were elimination of downtime, improvement of production flow, higher productivity as well as reduced backlog and elimination of product wastage.

Lean research in automotive industry is still valuable and up to date. Recent study carried out by Gaspar and Leal study [30], describes application of shop floor management model as presented by Hanenkamp, and defined a guideline dealing with sustainability of lean tools and philosophies in a manufacturing environment. Another study presented by Jagmeet Singh and Harwinder Singh [31], describes implementation of value stream mapping in a manufacturing company which is producing automotive suspension and fastening components and proved process improvement in terms of cycle time and level of work in process. Application of lean tools for waste reduction in steel industry is described in case study by Furman and Malysa [32]. A case study of lean implementation in plastic industry, specifically application of SMED (single minute exchange of die), lean tool for reduction of preparation time is presented by Reyes et al. [33]. The authors of a study conducted in Mexico also argue that lean is still one of the most important approaches in improving production [34]. They developed an instrument based on critical success factors to evaluate the implementation of lean tools, specifically in this study, for transportation equipment manufacturing subsector. Research about importance of implementation of lean and critical factors for implementing lean in Iranian industry was presented by Zahrae [35].

Lean has proven successful also in construction and shipbuilding industry. The authors of [36] have described the case study of implementation of lean in the bidding phase of construction process and found that it can benefit from lean. Lean has also found its application in the shipbuilding industry. Avad et al. have presented the study of possibilities of lean thinking implementation in construction industry. The objective was to improve building productivity. Results of productivity improvements with the approach presented were more sustainable as well as the cost and waste reduction [37]. The case study of introducing lean practice in the Croatian shipbuilding industry, by value stream mapping is presented in [38]. What the barriers of implantation of lean in shipbuilding industry are, specifically on the example on the shipbuilding industry in Singapore is well described in research paper [39]. Authors tried to explain the barriers to lean manufacturing as well as provide guidance for adopting lean practice in the shipbuilding industry.

In order to help various industries in implementing lean, a very interesting question is which lean tools and methods help the most to achieve the organizational goal. Thus, [40] have conducted review of 70 articles in 21 journals and have found that value stream mapping and DMAIC are the most widely used tools in all types of industries. They are followed by SMED and 5S. DMAIC is basically Six Sigma tool, while all other mentioned are lean tools. These findings could help other companies in deciding which direction to take when considering implementing lean [40].

1.1.3. Lean and Productivity

The goal of any lean implementation is to improve the organization processes and the efficiency of processes, which can be measured by productivity. The implementation of lean in small and medium enterprises and how it affected production productivity is presented in [5]. Authors have reported productivity improvement of productivity by 3900 additional units per month. In [6] authors presented a case study of applying lean in medium scale pump manufacturing. After adopting various lean techniques, mainly, value stream mapping, takt time and line balancing, authors reported improvement of assembly line efficiency up to 97%, as well as reductio of lead time about 13%. A similar case study of the application of lean production in small series production company is presented in [7]. After analyzing and eliminating waste, productivity has been improved, as well as lead time [7]. The application of lean tools, value stream mapping and waste elimination in the context of increased productivity is presented also in [8,9].

1.1.4. Pull Control Mechanisms

As previously explained, in practice, Kanban is often the first association when pull principle is considered. It was developed from the beginning of TPS [3], and later, when TPS started to spread in western countries and different types of manufacturing industries,

other pull mechanisms were developed. Three of them, besides the Kanban, are the focus of this study and they are Conwip, Hybrid Kanban/Conwip and DBR.

Conwip was developed by Spearman et al. [41]. It is a pull mechanism that limits the total amount of work in process as communication cards only exists between the finish goods warehouse and the first operation, whereas in Kanban communication cards flow between every workstation (every operation) upstream in the production process. Conwip is the abbreviation of "Constant Work in Process", the name that describes the essence of this pull mechanism [41].

Bonvik et al. proposed a new mechanism and called it Hybrid Conwip/Kanban as it combines communication rules both from Conwip and Kanban, thus communication exist both between warehouse and the first station but also between every station upstream in the process. They state that the advantage of the Hybrid Conwip/Kanban is in the processes with more workstations and more variability in the process but also the processes with bottleneck [13].

DBR is developed by Goldratt in his Theory of Constraints. The idea is that the signal for the beginning of processing a new item is sent from the bottleneck buffer to the first workstation in the production process [15].

While some of the studies of pull mechanisms investigate single-stage production processes [42] others investigated multistage processes, mostly with single product production [43–47]. Some articles describe case studies of implantation of pull control mechanisms [48] describes the development of two different Conwip approaches for bicycle chain manufacturing. They have simulated and compared these two approaches with the existing one and found that one outperforms by 42 percent and another by 50 percent regarding lead time. In [49] a case study of implementation of Hybrid Kanban/Conwip mechanism in high-variety/low-volume production process is presented and an increase of 38 percent in inventory turnover is described.

In addition, majority of studies deal with discrete production systems, but interesting findings regarding pull and its possibilities for process industry are presented in the research of Stevenson and Found who have gained important insights into the importance of pull and flow in process industries and its impact on production service, waste and utilization [50]. Very useful findings were gained in the study by Gayer et al. who researched applicability of pull in three different contexts, namely manufacturing, healthcare and construction. They have developed a method for assessment of pull production system according to twenty-three parameters divided in three groups: design, stability, and control [51]. In addition, Aldas et al. have investigated Kanban, Conwip and DBR by simulating production process in the textile industry and concluded with the preference of Kanban over Conwip and DBR [52]. Piplani and Ang, [53], compared Base Stock, Traditional Kanban Control System and Extended Kanban Control System (both dedicated and shared type) by simulation using common total cost measure as a performance measure for comparison. They presented procedures for optimizing multiple product Kanban control systems Numerical results show that the dedicated and shared-extended Kanban control systems outperform the other two systems [53].

2. Materials and Methods

Since the focus of this study was to investigate the influence of bottleneck on productivity of production processes controlled by different pull mechanisms, first the pull mechanisms themselves had to be defined. Bicheno found that Kanban, Conwip and DBR are three the most widely used pull production control mechanisms [14]. Review of the literature revealed the advantages also of Hybrid Kanban/Conwip; thus, these four mechanisms were researched in this study.

Kanban in Japanese means "card", and in TPS it was used to manage flow of material through the production process. In the production process controlled by Kanban cards, production is triggered by a demand. The operation stations send the signal (Kanban card) to the upstream workstation to replace the part that was just used. Hopp and Spearman

argue that there is a difference in installing and implementing Kanban and that the Kanban is very often considered as simple, but they state that the idea of Kanban is simple, and implementation is not. That is so because there are prerequisites for implementing Kanban in the process [54].

If production line consisting of two workplaces (two stages of the production process) where the process is controlled by a simple Kanban control mechanism is considered, the process of production control look as follows.

In the initial state, in the i-th stage of the production process, the Bi buffer contains k_i semi-finished products, where each semi-finished product has one Kanban card attached. When the demand from the customer arrives, the request goes to line D and withdraws the finished product from B_2. At this point, there are two possibilities:

- If there is a finished product in B_2, it is forwarded to the customer after the Kanban k_2 previously attached to it is separated from it. That Kanban is transferred to buffer of Kanban cards, K_2, which is a signal to produce a new piece of semi-finished product in stage 2;
- If there is no finished product in B_2, the request is withdrawn and put on hold until the finished product arrives in B_2. As soon as the finished product arrives, it is delivered to the customer and Kanban goes to K_2;

When the Kanban card arrives in K_2 it authorizes the start of production of a new product in stage 2. Here, again, two situations can occur:

- If a semi-finished product is available in the B_1 buffer, Kanban k_1 is immediately removed and k_2 is attached to that product. Then, the product and k_2 go together to workplace 2. Kanban k_1 is transferred to K_1 buffer which authorizes starting production on WP_1;
- If a semi-finished product is not available in the MS_1 buffer, Kanban card of the stage 2, k_2, will wait until new semi-finished product is available in MS_1 [55];

As in the Kanban system, in Conwip system signal cards control the level of WIP. Only, the signal cards do not go from one workstation to another, that is from one buffer to another, but from the last buffer (warehouse) to the first workstation Thus, Conwip cards control the overall amount of WIP, in contrast with Kanban mechanism controls WIP on every workstation.

Figure 1 represents the DBR mechanism, which is similar to Conwip, only the control cards do not travel from the last buffer to the first workstation, but from the bottleneck buffer to the first workstation, thus if the bottleneck is on the last workstation, then the DBR has similar characteristics (similar route) as Conwip.
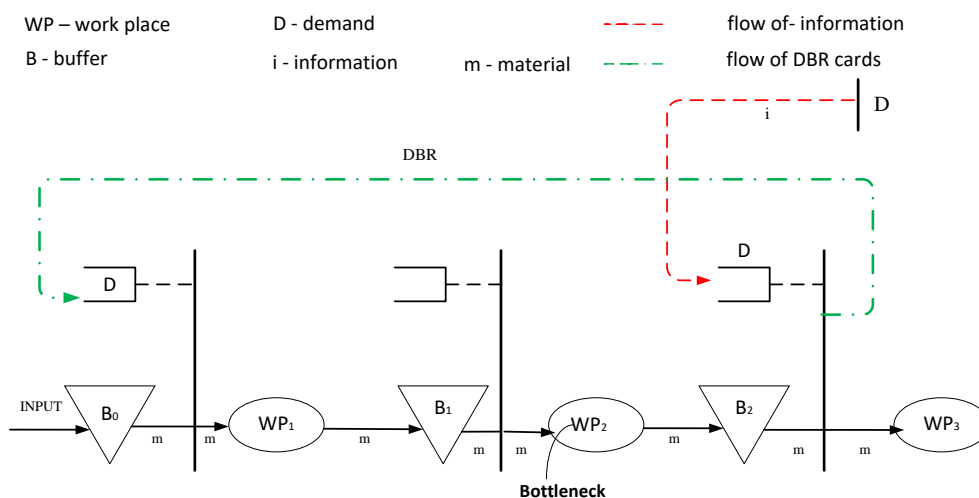

Figure 1. DBR control mechanism.

Hybrid is a combination of Kanban and Conwip, thus signal cards follow the same route as in Conwip, which is the global flow of information and also there is a route of the cards as in the Kanban system which is the local flow of information.

In order to answer the research questions simulation experimentation was conducted. Simulation is a commonly used research methodology. It is useful when the analysis on a real system is not possible due to one of the many possible reasons, such as time constraints, complexity, or unavailability of the real system at the given moment. Simulation allows for repeated observations of a model, by setting up the experiment, knowing where input conditions can change, and then initiating a set of simulation executions that produce a set of results [56]. In this research Design of Experiments and Response surface methodology was used. It is statistical method for setting and analyzing experiments, with the goal of analyzing the response, thus the dependent variable, by varying the factors or the input variables that are independent and controlled by experimenter [57]. After running experiments, mathematical models of regression functions are generated in order to show the relationship between productivity of production process, i.e., that is dependent variable in this case, and independent variables which are going to be described further in the text.

2.1. Simulation Model

The decision on the simulation model was made based on literature review, and it was found that the five-workstations production line can present enough different problems and relations in production processes [58–60]. One such model was used in a paper by Enss and Rogers and was used for validation [61]. The assumptions for the model are described below.

Every workstation is a different production operation. Between each operation, there is a buffer in which semi-finished products are stored after processing in the corresponding operation. Processing route of parts are as follows: production process starts at workstation 1, then it continuous, respectively, on workstations 2, 3, 4 and 5. The production sequence follows the FIFO (first in-first out) rule. Production is organized as a one-piece flow. The process never starves for material and finished products can immediately leave the process. Transport time between workstations is negligible, so it is for transfer of Kanban, Conwip and DBR cards. The Kanban system is modeled as a single-card Kanban system. The processing time on every workstation was 60 min, as in the paper [61]. This processing time can be found in studies dealing with similar problems [46,47,61–63] A lognormal distribution was used to generate processing time values. Possible stoppages are modeled by the randomness of production time. The set-up time is not the subject of this research, since the single product production is observed. Simulation run was 117,000 h (corresponds to one year). These assumptions are consistent with the previous studies [58,61,64–66]. Simulation was conducted in software Matlab, in its features for simulation Simulink and Simevents [67]. Simevents is a feature in Simulink for discrete simulation.

Validation of the Model

For the validation of the simulation model, three validation techniques ware performed. The first one is Comparison to other models technique and the other one is Extreme condition test technique. Furthermore, all models were confirmed by Face validation in the way that colleagues from the same field of research examined them and confirmed their validity [64].

Since in the Enss and Rogers paper Push and Conwip were modeled, in the model for this study, first the Conwip was modeled with the same set up and that is that processing time was stochastic and defined by coefficient of variation c_p. The distribution used was Gamma distribution. The number of Conwip cards was set to be the same [61]. The results of comparison are shown in the Table 1.

Table 1. Validation of the model.

Factors	Results-Matlab	Results for Comparison [61]	Difference, %
Throughput-Conwip, pcs/min	0.618	0.605	2.1

Kanban, Hybrid Conwip/Kanban and DBR were validated by Extreme condition test. The first extreme condition was extremely long operation time on the second workstation (85,000 min which is 80% of the whole simulation run). The results for every mechanism were that only one product came out of the process which is expected since the second operation took 80% of time of the simulation run. The second extreme condition was setting the number of control cards to zero at the one workstation in the case of Kanban and Hybrid, and in the case of DBR, extreme condition was the overall number of cards set to be zero. In every case the output was zero, meaning that no product was produced and that was expected since there were no cards that would trigger the production. All of these results feed into the assumption that the production process was well modeled.

2.2. Experiment Set Up

Since the focus of this study was the influence of bottleneck on productivity of production process controlled by different production control policies, bottleneck was the main independent variable. The other independent variables ware variability of production process, processing time and number of control cards of a pull control mechanism. Variability was expressed by the coefficient of variation.

One of the reasons the variability and the number of cards is chosen as a factor of the influence is strong relation between the variability (variable cycle time) on productivity [11]. Particularly, if the production process has variable cycle time influenced by many reasons, buffers (which are defined by the number of control cards in the process) provide production flow without stoppages in a way that it prevents the customer operation starving with material to process if the supplier operation is in shortage. In addition, it prevents stopping supplier operation if the subsequent operation cannot process a new part [11]. This is why variability is one of explored factors in this simulation study, as well as that number of control cards that define the level of WIP.

The levels of input parameters are shown in Table 2. The range of parameter value levels are consistent with those presented in literature [65,66].

Table 2. Factor levels.

Factors	Level 1	Level 2
Operation time	5	60
Coefficient of variation	0.25	0.86
Existence of a bottleneck in the process	NO	YES
Number of control cards	10	15

In order to define the relationship between parameters and response function simulation experiments are obtained and design of experiments is used. The Response surface method is applied to obtain mathematical model that define these relationships. According to Myers, Montgomery and Andersoon-Cook, [68], there is no standard response surface design for the case when some of the variables are categorical variables. In this case general full two-level factorial design was conducted and in Design-Expert 7, software used for making design and perform analysis, the design for combination of categorical and numerical variables is multilevel categorical [69]. Since there are four input parameters for this experiment, and five replication of two-level factorial design, 80 runs for each pull control mechanism were performed. This number of runs was performed for all four mechanisms,

thus in total 320 runs was carried out. The order of execution of the experiment plan was random and generated by the Design-Expert 7 program. In Appendices A and B are presented experimental tables (Tables A1–A7) which present all runs with standard order generated by Design expert, as well as responses gathered trough simulations. Due to the characteristics of the simulation model, the number of cards in the experiment are defined per workstation. Thus, for a total of 10 cards in the process, since the process consists of five workstations, the value of this parameter is two cards per workstation. For the case of 15 cards in the process, the value of the parameter is three cards per workstation (Appendix A).

3. Results

In this chapter the results of data analysis will be presented. The results speak of the dependence of productivity on bottleneck, variability, processing time and the pull control mechanism, specifically, the number of control cards for each mechanism. The data gathered by simulation experimentation were processed in order to obtain a mathematical model that describes that dependence. A total of eight regression functions were generated, two for each of the mechanisms (one for the process with bottleneck and one for the process without bottleneck), respectively, for Kanban, Conwip, Hybrid and DBR.

Analysis of variance (ANOVA) was performed to determine the significance of the factors and the response function was developed by regression analysis. The factors of model A, B, C and D were as follows:

- A—coefficient of variation.
- B—operation time;
- C—existence of a bottleneck;
- D—number of control cards.

For every mechanism, a table of analysis of variance (ANOVA) shows that the models are significant (Tables 3–6). This is indicated by F-value, but also *p*-value. So, the hypothesis that variability, processing time, bottleneck and number of control cards do not affect the productivity is rejected. *p*-values for every parameter of the model showed significance of the parameters but also some of their interactions (Tables 3–6).

Table 3. ANOVA-Kanban.

Source of Variation	Sum of Squares	Df	Mean Square	F-Value	*p*-Value	Significance
Model	1896.68	13	145.90	3.12×10^5	<0.0001	significant
Factors:						
A	3.08	1	3.08	6594.23	<0.0001	significant
B	1803.70	1	1803.70	386,000	<0.0001	significant
C	49.09	1	49.09	105×10^5	<0.0001	significant
D	0.0050	1	0.0050	10.72	0.0017	significant
AB	0.1545	1	0.1545	330.91	<0.0001	significant
AC	0.0564	1	0.0564	120.90	<0.0001	significant
AD	0.0052	1	0.0052	11.05	0.0014	significant
BC	40.52	1	40.52	86,813.54	<0.0001	significant
BD	0.0056	1	0.0056	11.94	0.0010	significant
CD	0.0147	1	0.0147	31.54	<0.0001	significant
ABC	0.0246	1	0.0246	52.70	<0.0001	significant
ABD	0.0050	1	0.0050	10.82	<0.0016	significant
ACD	0.0198	1	0.0198	42.38	<0.0001	significant
Residual	0.0308	66	0.0005			significant
Deviation of the model	0.0009	2	0.0004	0.9300	0.3998	not significant

Df—degree of freedom.

Table 4. ANOVA-Conwip.

Source of Variation	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Model	1012.62	12	84.38	2.757×10^5	<0.0001	significant
Factors:						
A	1.72	1	1.72	5606.23	<0.0001	significant
B	972.16	1	972.16	3.176×10^6	<0.0001	significant
C	21.87	1	21.87	71,453.50	<0.0001	significant
D	0.0095	1	0.0095	30.99	<0.0001	significant
AB	0.0241	1	0.0241	78.87	<0.0001	significant
AC	0.0578	1	0.0578	188.66	<0.0001	significant
AD	0.0100	1	0.0100	32.79	<0.0001	significant
BC	16.74	1	16.74	54,685.03	<0.0001	significant
BD	0.0021	1	0.0021	6.97	0.0972	significant
CD	0.0069	1	0.0069	22.56	<0.0001	significant
ABC	0.0139	1	0.0139	45.34	<0.0001	significant
ACD	0.0036	1	0.0036	11.62	0.0006	significant
Residual	0.0205	67	0.0005			significant
Deviation of the model	0.0014	3	0.0003	1.61	0.5633	not significant

Table 5. ANOVA-Hybrid Kanban/Conwip.

Source of Variation	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Model	703.33	13	54.10	2.949×10^5	<0.0001	significant
Factors:						
A	675.94	1	675.94	3.684×10^6	<0.0001	significant
B	13.66	1	13.66	74,455.62	<0.0001	significant
C	0.0081	1	0.0081	44.01	<0.0001	significant
D	0.0146	1	0.0146	28.68	<0.0001	significant
AB	0.0053	1	0.0053	28.84	<0.0001	significant
AC	0.0484	1	0.0484	263.63	<0.0001	significant
AD	0.0044	1	0.0044	23.84	<0.0001	significant
BC	9.77	1	9.77	53,259.45	<0.0001	significant
BD	0.0020	1	0.0020	10.68	0.0017	significant
CD	0.0081	1	0.0081	44.10	<0.0001	significant
ABC	0.0099	1	0.0099	54.16	<0.0001	significant
ABD	0.0015	1	0.0015	8.22	0.0056	significant
ACD	0.0049	1	0.0049	26.76	<0.0001	significant
Residual	0.0121	66	0.0002			significant
Deviation of the model	0.0006	2	0.0003	1.81	0.1726	not significant

Table 6. ANOVA-DBR.

Source of Variation	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance
Model	1897.72	8	237.21	1.126×10^6	<0.0001	significant
Factors:						
A	2.61	1	2.61	14,245.47	<0.0001	significant
B	1811.56	1	1811.56	9.886×10^6	<0.0001	significant
C	45.74	1	45.74	2.496×10^5	<0.0001	significant
D	0.0025	1	0.0025	13.39	0.0005	significant
AB	0.1530	1	0.1530	835.16	<0.0001	significant
AC	0.1313	1	0.1313	716.53	<0.0001	significant
AD	0.0030	1	0.0030	16.61	0.0001	significant
BC	37.52	1	37.52	2.048×10^5	<0.0001	significant
Residual	0.0133	71	0.0002			significant
Deviation of the model	0.0017	7	0.0002	1.36	0.2362	not significant

The deviations of the models, as seen in the tables were not significant, which was indicated by F-value, meaning that the models describe the phenomenon well enough.

After the analysis of variance, regression analysis was carried out for all mechanisms. All the values gather by regression analysis indicated significance of generated model and that the regression model is different from a random phenomenon. [69].

The generated model for Kanban was as follows:

$$P_{\text{Kanban-BN}} = 9.85712 - 0.844392\text{Cv} - 0.150878\text{T} + 0.003959\text{Nr} + 0.008078\text{CvT} + 0.001504\text{CvNr} \tag{1}$$

$$P_{\text{Kanban}} = 13.13354 - 0.936188\text{Cv} - 0.200347\text{T} - 0.002739\text{Nr} + 0.003491\text{CvT} + 0.034448\text{CvNr} \tag{2}$$

Variable from Equations (1) and (2) are as follows:

- $P_{\text{Kanban-BN}}$—productivity for the process with bottleneck, controlled by Kanban, min;
- P_{Kanban}—lead time for the process with without bottleneck, controlled by Kanban, min;
- Cv—coefficient of variation;
- T—processing time;
- Nr—number of control cards;

Ratio of maximum and minimum measured values, in cases of Conwip and Hybrid Kanban/Conwip mechanism measured value was greater than 10, so transformation of data was required [69]. In this way, the homogeneity of variance over the experimental space is satisfied [70]. Data were transformed according to Equation (3).

$$y' = (y + k)^\lambda, k = 0, \lambda = 0.88 \text{ for Conwip}, \lambda = 0.88 \text{ for Hybrid Kanban/Conwip} \tag{3}$$

Variables in the Equation (3) are:

- y'—transformed value
- y—real value

Regression functions for Conwip and Hybrid Kanban/Conwip mechanism are:

$$(P_{\text{Conwip}})^{0.88} = 9.82046 - 0.877525\text{Cv} - 0.144614\text{T} - 0.036874\text{Nr} + 0.0051\text{CvT} + 0.117177\text{CvNr} + 0.000376\text{TBr} \tag{4}$$

$$(P_{\text{Conwip-BN}})^{0.88} = 7.6239 - 0.584773\text{Cv} - 0.113088\text{T} - 0.025503\text{Nr} + 0.003642\text{CvT} + 0.029719\text{CvNr} + 0.000376\text{TNr} \tag{5}$$

$$(P_{\text{Hybrid}})^{0.81} = 8.16982 - 0.563684\text{Cv} - 0.116823\text{T} - 0.008266\text{Nr} - 0.004897\text{CvT} + 0.066395\text{CvNr} - 0.000215\text{TNr} + 0.001038\text{CvTNr} \tag{6}$$

$$(P_{\text{Hybrid-BN}})^{0.81} = 6.43031 - 0.231142\text{Cv} - 0.092833\text{T} + 0.008571\text{Nr} - 0.002235\text{CvT} - 0.036615\text{CvNr} - 0.000215\text{TNr} + 0.001038\text{CvTNr} \tag{7}$$

Variable from Equations (4)–(7) are as follows:

- $P_{\text{Conwip-BN}}$—productivity for the process with bottleneck, controlled by Conwip, min;
- P_{Conwip}—productivity for the process with without bottleneck, controlled by Conwip, min;
- $P_{\text{Hybrid-BN}}$—productivity for the process bottle neck, controlled by Hybrid Kanban/ Conwip, min;
- P_{Hybrid}—productivity for the process with without bottle neck, controlled by Hybrid Kanban/Conwip, mi n;
- C_V—coefficient of variation;
- T—processing time;
- Nr—number of control cards;

The values calculated by Equations (4)–(7) must be transformed by the Equation (8).

$$y = \sqrt[\lambda]{y'} \tag{8}$$

Regression functions for DBR mechanism are

$$P_{\text{DBR-BN}} = 9.88346 - 0.696599Cv - 0.151325T - 0.004601Nr + 0.005583CvT + 0.016574CvNr \tag{9}$$

$$P_{\text{DBR}} = 13.16724 - 0.961586Cv - 0.201172T + 0.004601Nr + 0.005583CvT + 0.016574CvNr \tag{10}$$

Variable from Equations (8) and (9) are as follows:

- $P_{\text{DBR-BN}}$—productivity for the process with bottle neck, controlled by DBR, min;
- P_{DBR}—productivity for the process with without bottle neck, controlled by DBR, min;
- C_V—coefficient of variation;
- T—processing time;
- Nr—number of control cards;

4. Discussion

By using the regression function presented above, it is possible to calculate productivity levels for all four mechanisms, whether bottleneck exists in the process or not, and for a given current condition of a production process in terms of variability, processing time and the desired level of WIP. By comparing of calculated values, one can decide which control mechanism to choose. Figure 2 presents just one of the possible combinations of independent parameters and level of productivity for that specific condition. The influence of the bottleneck in the process is obvious and for the same level of parameters, variability, processing time and WIP, the same pull control mechanism will not achieve the optimal level of productivity in the process with and without bottleneck (Figure 2a,b). Therefore, for this specific case, for the process with bottleneck DBR would be better choice, while for the process without bottleneck the better choice would be the Conwip mechanism.

(a) (b)
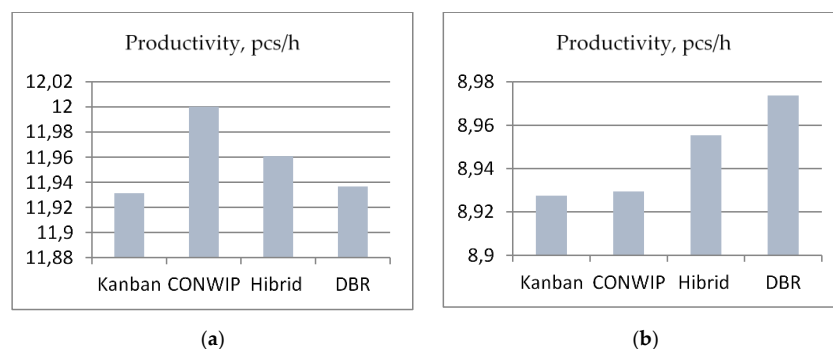
Figure 2. Comparison of effectiveness of pull control mechanisms (**a**) Productivity for set of parameters: za Cv = 0.25, T = 5 min, WIP = 15, for the process without bottleneck (**b**) Productivity for set of parameters: za Cv = 0.25, T = 5 min, WIP = 15, for the process with bottleneck.

For further check and discussion, let us look at a production process with higher variability, Cv = 1.25, and WIP = 5 and the process with bottleneck. Processing time is 5 min as above. Figure 3 presents the levels of productivity for this combination of parameters. In this case with bottleneck Hybrid Kanban/Conwip would be better choice.
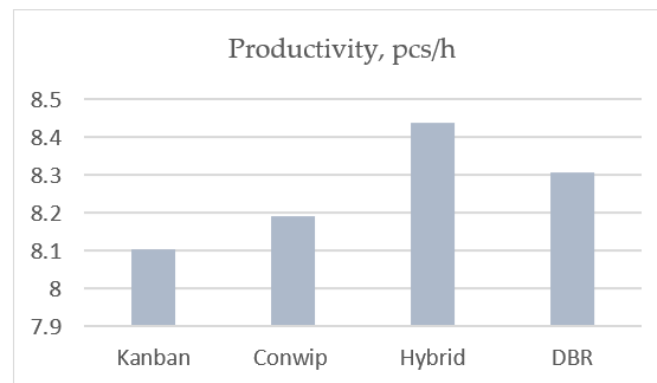
Figure 3. Comparison of the effectiveness of pull control mechanisms in the process with bottleneck for Cv = 1.25, t = 5min, WIP = 5.

The advantage and novelty of this study is that it is useful as u guideline for many other combinations of levels of independent parameters which are different for different production facilities. This could help managers in this field in making decision on which production control mechanisms to implement.

In practice, lean implementation is not that simple task. There are well known general steps in transforming production processes according to lean principles. Many lean implementation projects start with great success but do not succeed in greater extant, rather slow down or stop due to challenges that emerge. Pull principle is a big challenge for many companies and demands a lot of prerequisites in order to be achieved and that is well described in literature [3,71].

One of the decisions that have to be made when introducing pull in the production is which production control mechanism to use. Effectiveness of pull control mechanisms under various production condition is not the same and for industrial practitioners it is not always clear which control mechanism would be suitable for their process. The process of implementation of pull production mechanisms can be significantly long and to test in real production and then make the decision mechanism to implement is impractical and expensive. Thus, findings gained from this study could help production managers to make decision and choose appropriate pull mechanism.

As was the initial assumption, the results of simulation experimentation showed that the existence of bottleneck in the process affects the efficiency of pull control mechanisms in terms of productivity. That is, one mechanism which is optimal for the process without bottleneck is not optimal for the process with bottleneck. It is also confirmed that for the different level of input parameters, namely variability, process time and number of control cards, different pull control mechanism contribute to better levels of productivity, thus if in the case of a bottleneck one mechanism for one setting of production parameters is optimal for another setting of parameters, also with bottleneck, that same mechanism will not be the best choice.

5. Conclusions

The focus of this study was to explore how the bottleneck influences effectiveness of pull control mechanisms in terms of production productivity in various production conditions, defined by different levels of variability in the production process, processing time and number of signal cards, which actually define the level of work-in-process, since every card is tied to one product at a time. Some previous studies have investigated the influence of bottleneck but not for these production conditions, nor for all of four

pull mechanisms researched in this study. In addition, this study gained, regression functions defining the dependence of productivity on all of these mentioned parameters. Regression functions were generated separately for each of the four control mechanisms, and, separately for the process with and the process without the bottleneck. Thus, a total of eight regression functions were generated. The influence of independent parameters, their main effects and interaction effects, on the dependent variable is different in all eight cases, which can be seen by reviewing the regression coefficients shown in Appendix B. This shows that for the same level of parameters the level of productivity will be different depending on the type of control mechanism under consideration. The same goes for the process with or without bottleneck. As shown in more detail in the Discussion section, by calculating the value of productivity, one can make a comparison and decide which control mechanism to choose for implementation. Thus, by knowing the current state of production process in terms of existence of bottleneck, level of variability, processing time and the desired level of work-in process, one can use those regression functions to find determine which pull control mechanism to use in their process. In addition, by knowing the current state of production process regarding bottleneck, variations in the process, level of work in process, industrial practitioners can, by using the knowledge from this study about influence of all these parameters on productivity, make a decision for an improvement goals in the process.

Authors of this study are aware that this type of decision is not a "one-way road", that is, that many other factors such as previous experience of the company in lean manufacturing in general as a mindset, but also experience in implementing pull principle, can influence the decision which pull control mechanism to use.

The limitation of this study is in that it has considered single-product production, so future studies could focus on researching multiple-product production, as well as different types of production processes other than serial production line explored in this study.

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Appendix A

Table A1. Experiment design table—KANBAN.

Std	Factor 1 A:Coeff. of var.	Factor 2 B:Process. time	Factor 3 C:Bottleneck	Factor 4 D:Num. of Cards	Response 1 Productivity
79	0.25	60	YES	5	0.7358
61	0.25	5	YES	5	8.91
12	0.86	60	NO	5	0.662511
24	0.86	60	YES	2	0.4687
56	0.86	60	YES	2	0.4798
2	0.86	5	NO	2	11.37
78	0.86	5	YES	5	8.4114
5	0.25	5	YES	2	8.89218
73	0.25	5	NO	5	11.9192

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	A:Coeff. of var.	B:Process. time	C:Bottleneck	D:Num. of Cards	Productivity
66	0.86	5	NO	2	11.391
47	0.25	60	YES	5	0.7261
51	0.25	60	NO	2	0.937762
75	0.25	60	NO	5	0.9615
54	0.86	5	YES	2	8.40368
22	0.86	5	YES	2	8.40368
69	0.25	5	YES	2	8.90216
14	0.86	5	YES	5	8.42742
43	0.25	60	NO	5	0.9594
67	0.25	60	NO	2	0.946778
32	0.86	60	YES	5	0.5497
44	0.86	60	NO	5	0.66613
1	0.25	5	NO	2	11.9043
6	0.86	5	YES	2	8.41359
68	0.86	60	NO	2	0.520305
23	0.25	60	YES	2	0.7266
21	0.25	5	YES	2	8.90216
25	0.25	5	NO	5	11.9262
35	0.25	60	NO	2	0.948248
46	0.86	5	YES	5	8.44544
42	0.86	5	NO	5	11.417
31	0.25	60	YES	5	0.7302
33	0.25	5	NO	2	11.9104
55	0.25	60	YES	2	0.7277
50	0.86	5	NO	2	11.41
17	0.25	5	NO	2	11.9161
19	0.25	60	NO	2	0.945308
80	0.86	60	YES	5	0.5251
49	0.25	5	NO	2	11.9161
16	0.86	60	YES	5	0.4861
41	0.25	5	NO	5	11.9352
71	0.25	60	YES	2	0.7261
28	0.86	60	NO	5	0.568699
7	0.25	60	YES	2	0.7323
52	0.86	60	NO	2	0.525112
13	0.25	5	YES	5	8.9276
63	0.25	60	YES	5	0.74
15	0.25	60	YES	5	0.7277
65	0.25	5	NO	2	11.9181
18	0.86	5	NO	2	11.41
74	0.86	5	NO	5	11.436
9	0.25	5	NO	5	11.9365
20	0.86	60	NO	2	0.537443
77	0.25	5	YES	5	8.9297
4	0.86	60	NO	2	0.539638
60	0.86	60	NO	5	0.605299
53	0.25	5	YES	2	8.91214
59	0.25	60	NO	5	0.962
3	0.25	60	NO	2	0.940212
64	0.86	60	YES	5	0.5425
72	0.86	60	YES	2	0.5113
37	0.25	5	YES	2	8.92212
62	0.86	5	YES	5	8.45244
76	0.86	60	NO	5	0.641898
48	0.86	60	YES	5	0.502

Table A1. *Cont.*

Std	Factor 1 A:Coeff. of var.	Factor 2 B:Process. time	Factor 3 C:Bottleneck	Factor 4 D:Num. of Cards	Response 1 Productivity
45	0.25	5	YES	5	8.934
70	0.86	5	YES	2	8.43341
38	0.86	5	YES	2	8.45323
58	0.86	5	NO	5	11.465
11	0.25	60	NO	5	0.961
10	0.86	5	NO	5	11.496
29	0.25	5	YES	5	8.937
40	0.86	60	YES	2	0.5225
39	0.25	60	YES	2	0.7246
34	0.86	5	NO	2	11.43
30	0.86	5	YES	5	8.45244
26	0.86	5	NO	5	11.533
8	0.86	60	YES	2	0.5471
57	0.25	5	NO	5	11.9447
27	0.25	60	NO	5	0.9538
36	0.86	60	NO	2	0.551446

Std-standard order.

Table A2. Experiment design table—CONWIP.

Std	Factor 1 A:Coeff. of var.	Factor 2 B:Process. Time	Factor 3 C:Bottleneck	Factor 4 D:Num. of Cards	Response 1 Productivity
56	0.86	60	YES	2	0.5149
51	0.25	60	NO	2	0.9728
47	0.25	60	YES	3	0.7358
75	0.25	60	NO	3	0.971115
61	0.25	5	YES	3	8.935
64	0.86	60	YES	3	0.588179
24	0.86	60	YES	2	0.5251
3	0.25	60	NO	2	0.9656
18	0.86	5	NO	2	11.364
57	0.25	5	NO	3	11.93
21	0.25	5	YES	2	8.974
17	0.25	5	NO	2	11.92
35	0.25	60	NO	2	0.9579
76	0.86	60	NO	3	0.672078
26	0.86	5	NO	3	11.41
40	0.86	60	YES	2	0.5221
22	0.86	5	YES	2	8.48
31	0.25	60	YES	3	0.7261
78	0.86	5	YES	3	8.462
27	0.25	60	NO	3	0.967075
79	0.25	60	YES	3	0.7302
10	0.86	5	NO	3	11.42
50	0.86	5	NO	2	11.326
16	0.86	60	YES	3	0.561857
11	0.25	60	NO	3	0.969696
25	0.25	5	NO	3	11.94
73	0.25	5	NO	3	11.94

Table A2. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	**A:Coeff. of var.**	**B:Process. Time**	**C:Bottleneck**	**D:Num. of Cards**	**Productivity**
19	0.25	60	NO	2	0.959
55	0.25	60	YES	2	0.7354
29	0.25	5	YES	3	8.946
53	0.25	5	YES	2	8.956
5	0.25	5	YES	2	8.943
6	0.86	5	YES	2	8.48
49	0.25	5	NO	2	11.93
1	0.25	5	NO	2	11.937
74	0.86	5	NO	3	11.45
36	0.86	60	NO	2	0.5327
48	0.86	60	YES	3	0.520127
43	0.25	60	NO	3	0.968688
67	0.25	60	NO	2	0.957
12	0.86	60	NO	3	0.67575
30	0.86	5	YES	3	8.503
68	0.86	60	NO	2	0.5376
4	0.86	60	NO	2	0.5503
54	0.86	5	YES	2	8.49
44	0.86	60	NO	3	0.576912
33	0.25	5	NO	2	11.94
41	0.25	5	NO	3	11.94
60	0.86	60	NO	3	0.61404
52	0.86	60	NO	2	0.5525
63	0.25	60	YES	3	0.74
34	0.86	5	NO	2	11.334
77	0.25	5	YES	3	8.927
39	0.25	60	YES	2	0.7262
14	0.86	5	YES	3	8.468
80	0.86	60	YES	3	0.580475
42	0.86	5	NO	3	11.48
2	0.86	5	NO	2	11.364
62	0.86	5	YES	3	8.487
38	0.86	5	YES	2	8.51
65	0.25	5	NO	2	11.937
23	0.25	60	YES	2	0.7303
8	0.86	60	YES	2	0.5154
69	0.25	5	YES	2	8.945
66	0.86	5	NO	2	11.328
71	0.25	60	YES	2	0.7215
20	0.86	60	NO	2	0.5646
28	0.86	60	NO	3	0.651168
45	0.25	5	YES	3	8.925
59	0.25	60	NO	3	0.96143
7	0.25	60	YES	2	0.7277
32	0.86	60	YES	3	0.53714
13	0.25	5	YES	3	8.932
46	0.86	5	YES	3	8.547
70	0.86	5	YES	2	8.59
9	0.25	5	NO	3	11.95
72	0.86	60	YES	2	0.521
15	0.25	60	YES	3	0.7277
37	0.25	5	YES	2	8.959
58	0.86	5	NO	3	11.47

Std—standard order.

Table A3. Experiment design table—Hybrid Kanban/Conwip.

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	A:Coeff. of var.	B:Process. Time	C:Bottleneck	D:Num. of Cards	Productivity
64	0.86	60	YES	3	0.5568
26	0.86	5	NO	3	11.4524
74	0.86	5	NO	3	11.4715
2	0.86	5	NO	2	11.3676
22	0.86	5	YES	2	8.593
32	0.86	60	YES	3	0.5319
48	0.86	60	YES	3	0.4924
71	0.25	60	YES	2	0.7276
17	0.25	5	NO	2	11.9389
5	0.25	5	YES	2	8.9441
46	0.86	5	YES	3	8.552
30	0.86	5	YES	3	8.568
66	0.86	5	NO	2	11.3415
53	0.25	5	YES	2	8.9558
78	0.86	5	YES	3	8.587
25	0.25	5	NO	3	0.7328
14	0.86	5	YES	3	8.594
44	0.86	60	NO	3	0.647
70	0.86	5	YES	2	8.626
11	0.25	60	NO	3	11.977
79	0.25	60	YES	3	8.961
21	0.25	5	YES	2	8.9554
50	0.86	5	NO	2	11.4522
9	0.25	5	NO	3	11.9514
37	0.25	5	YES	2	8.9657
31	0.25	60	YES	3	0.728059
18	0.86	5	NO	2	11.449
3	0.25	60	NO	2	0.9625
55	0.25	60	YES	2	0.7269
57	0.25	5	NO	3	11.9584
42	0.86	5	NO	3	11.5005
29	0.25	5	YES	3	0.9661
20	0.86	60	NO	2	0.5161
65	0.25	5	NO	2	11.9615
33	0.25	5	NO	2	11.947
16	0.86	60	YES	3	0.5495
15	0.25	60	YES	3	0.732221
10	0.86	5	NO	3	11.5316
68	0.86	60	NO	2	0.5209
8	0.86	60	YES	2	0.522
59	0.25	60	NO	3	0.974
12	0.86	60	NO	3	0.6505
75	0.25	60	NO	3	0.9718
63	0.25	60	YES	3	0.742066
28	0.86	60	NO	3	0.6554
61	0.25	5	YES	3	8.934
39	0.25	60	YES	2	0.722
60	0.86	60	NO	3	0.6111
62	0.86	5	YES	3	8.594
6	0.86	5	YES	2	8.5958
1	0.25	5	NO	2	11.923
23	0.25	60	YES	2	0.7256
36	0.86	60	NO	2	0.5331

Table A3. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	A:Coeff. of var.	B:Process. Time	C:Bottleneck	D:Num. of Cards	Productivity
7	0.25	60	YES	2	0.722
43	0.25	60	NO	3	0.9745
38	0.86	5	YES	2	8.6092
24	0.86	60	YES	2	0.5123
52	0.86	60	NO	2	0.5353
54	0.86	5	YES	2	8.586
49	0.25	5	NO	2	11.9317
34	0.86	5	NO	2	11.4723
41	0.25	5	NO	3	11.9674
58	0.86	5	NO	3	11.5688
56	0.86	60	YES	2	0.5184
4	0.86	60	NO	2	0.547
19	0.25	60	NO	2	0.9656
69	0.25	5	YES	2	8.9757
72	0.86	60	YES	2	0.5077
80	0.86	60	YES	3	0.5085
77	0.25	5	YES	3	8.952
47	0.25	60	YES	3	0.729684
35	0.25	60	NO	2	0.9683
51	0.25	60	NO	2	0.96154
40	0.86	60	YES	2	0.5205
73	0.25	5	NO	3	11.9687
13	0.25	5	YES	3	8.954
27	0.25	60	NO	3	0.9734
45	0.25	5	YES	3	8.958
76	0.86	60	NO	3	0.6269
67	0.25	60	NO	2	0.95691

Std—standard order.

Table A4. Experiment design table—DBR.

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	A:Coeff. of var.	B:Process. Time	C:Bottleneck	D:Num. of Cards	Productivity
79	0.25	60	YES	3.5	0.747939
18	0.86	5	NO	2.25	11.387
20	0.86	60	NO	2.25	0.6164
59	0.25	60	NO	3.5	0.955385
32	0.86	60	YES	3.5	0.571312
47	0.25	60	YES	3.5	0.75639
26	0.86	5	NO	3.5	11.421
73	0.25	5	NO	3.5	11.937
23	0.25	60	YES	2.25	0.736492
38	0.86	5	YES	2.25	8.595
55	0.25	60	YES	2.25	0.728715
40	0.86	60	YES	2.25	0.5395
28	0.86	60	NO	3.5	0.6
41	0.25	5	NO	3.5	11.931
9	0.25	5	NO	3.5	11.943
76	0.86	60	NO	3.5	0.630769
27	0.25	60	NO	3.5	0.964103
68	0.86	60	NO	2.25	0.5897
31	0.25	60	YES	3.5	0.73579

Table A4. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	A:Coeff. of var.	B:Process. Time	C:Bottleneck	D:Num. of Cards	Productivity
58	0.86	5	NO	3.5	11.412
30	0.86	5	YES	3.5	8.60618
36	0.86	60	NO	2.25	0.6144
4	0.86	60	NO	2.25	0.6036
10	0.86	5	NO	3.5	11.417
12	0.86	60	NO	3.5	0.577949
3	0.25	60	NO	2.25	0.961
70	0.86	5	YES	2.25	8.608
64	0.86	60	YES	3.5	0.562615
39	0.25	60	YES	2.25	0.731846
44	0.86	60	NO	3.5	0.663077
24	0.86	60	YES	2.25	0.5159
53	0.25	5	YES	2.25	8.987
19	0.25	60	NO	2.25	0.9595
14	0.86	5	YES	3.5	8.60618
78	0.86	5	YES	3.5	8.63924
72	0.86	60	YES	2.25	0.5323
62	0.86	5	YES	3.5	8.6172
52	0.86	60	NO	2.25	0.5856
49	0.25	5	NO	2.25	11.94
2	0.86	5	NO	2.25	11.423
42	0.86	5	NO	3.5	11.388
57	0.25	5	NO	3.5	11.937
54	0.86	5	YES	2.25	8.58
45	0.25	5	YES	3.5	8.95988
71	0.25	60	YES	2.25	0.739623
37	0.25	5	YES	2.25	8.9818
33	0.25	5	NO	2.25	11.96
66	0.86	5	NO	2.25	11.391
67	0.25	60	NO	2.25	0.9615
69	0.25	5	YES	2.25	8.98
48	0.86	60	YES	3.5	0.5512
22	0.86	5	YES	2.25	8.591
74	0.86	5	NO	3.5	11.431
13	0.25	5	YES	3.5	8.97191
34	0.86	5	NO	2.25	11.377
75	0.25	60	NO	3.5	0.963077
21	0.25	5	YES	2.25	8.9708
43	0.25	60	NO	3.5	0.962564
61	0.25	5	YES	3.5	8.97491
46	0.86	5	YES	3.5	8.63423
50	0.86	5	NO	2.25	11.417
60	0.86	60	NO	3.5	0.610256
11	0.25	60	NO	3.5	0.963077
29	0.25	5	YES	3.5	8.9679
7	0.25	60	YES	2.25	0.738613
17	0.25	5	NO	2.25	11.947
77	0.25	5	YES	3.5	8.96189
63	0.25	60	YES	3.5	0.742657
8	0.86	60	YES	2.25	0.5207
65	0.25	5	NO	2.25	11.923
5	0.25	5	YES	2.25	8.976
16	0.86	60	YES	3.5	0.578379
56	0.86	60	YES	2.25	0.5221
80	0.86	60	YES	3.5	0.559897

Table A4. *Cont.*

Std	Factor 1 A:Coeff. of var.	Factor 2 B:Process. Time	Factor 3 C:Bottleneck	Factor 4 D:Num. of Cards	Response 1 Productivity
15	0.25	60	YES	3.5	0.745826
6	0.86	5	YES	2.25	8.6
51	0.25	60	NO	2.25	0.9538
1	0.25	5	NO	2.25	11.931
25	0.25	5	NO	3.5	11.935
35	0.25	60	NO	2.25	0.9738

Std—standard order.

Appendix B

Table A5. Regression coefficient for coded factors.

	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD
Kanban	5.44	−0.195	−4.74	−0.7878	0.00159	0.0485	0.0191	0.0082	0.7152	-	−0.0087	0.0192	-	−0.0075
(Conwip)$^{0.88}$	4.22	−0.1465	−3.49	−0.5229	0.0109	0.0174	0.0269	0.0112	0.4574	0.0052	−0.0093	0.0132	-	−0.0067
(Hybrid)$^{0.81}$	3.66	−0.1195	−2.91	−0.414	0.0101	−0.0081	0.0246	0.0074	O.3502	0.005	−0.0101	0.0112	0.0044	−0.0079
DBR	5.47	−0.1806	−4.76	−0.7561	0.0055	0.0437	0.0405	0.0062	0.6848	-	-	-	-	-

Table A6. Regression coefficient for real factors-process with bottleneck.

	Cv	T	Nr	CvT	CvNr	TNr	CvTNr
Kanban	9.85712	−0.844392	−0.150878	0.003959	0.008078	0.001504	-	-
(Conwip)$^{0.88}$	7.6239	−0.584773	−0.113088	−0.025503	0.003642	0.029719	0.000376	-
(Hybrid)$^{0.81}$	6.43031	−0.231142	−0.092833	0.008571	−0.002235	−0.036615	−0.000215	0.001038
DBR	9.88346	−0.696599	−0.151325	−0.004601	0.005583	0.016574	-	-

Table A7. Regression coefficient for real factors-process without bottleneck.

	Cv	T	Nr	CvT	CvNr	TNr	CvTNr
Kanban	13.13354	−0.936188	−0.200347	−0.002739	0.003491	0.034448	-	-
(Conwip)$^{0.88}$	9.82046	−0.877525	−0.144614	−0.036874	0.0051	0.117177	0.000376	0.000376
(Hybrid)$^{0.81}$	8.16982	−0.563684	−0.116823	−0.008266	−0.004897	0.066395	0.000215	0.001038
DBR	13.16724	−0.961586	−0.201172	0.004601	0.005583	0.016574		

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