Simulation of a Flexible and Adaptable One-Piece-Flow Assembly Line Based on a Process Flow of Colored and Timed Petri Nets

Benedikt A. Latos
Peyman Kalantar
Philipp M. Przybysz
Susanne Mütze-Niewöhner
Institute of Industrial Engineering
and Ergonomics
RWTH Aachen University
Bergdriesch 27
52062 Aachen
Germany
E-mail: b.latos@iaw.rwth-aachen.de

Christoph Holtkötter
Jan Brinkjans
Miele & Cie. KG
Carl-Miele-Straße 29
33325 Gütersloh
Germany

KEYWORDS
Production, Discrete simulation, Decision-making, Process-oriented, Stochastic

ABSTRACT

The growing demand for individualized consumer goods and the increase in production volume variations brings significant challenges for manufacturing enterprises so that engineering teams are assigned the task to find innovative production solutions to meet these requirements. Especially personnel-intensive assembly departments have to be designed to meet the challenge of enabling such a flexible production whilst still maintaining good working conditions. When comparing different assembly concepts, simulation can help to explore the behavior and implications of different innovative assembly concepts. By doing so, set up cost can massively be reduced since the system can be launched in a more efficient manner. This paper presents the development of a simulation model based on a colored Petri Net flow chart. The area of application of this model is a manufacturer of white goods situated in Germany. The process-oriented and actor-integrated simulation model provides the possibility of simulating diverse scenarios when comparing various concepts in an early assembly line planning phase.

INTRODUCTION

It is essential for manufacturing companies to adopt to frequent market changes in order to remain competitive. The need for continuous product innovation, increase in product variants, shorter product lifecycles, fluctuating demands and handling unexpected requirements in recent years are a result of these increased dynamics (Spath et al. 2013). Assembly typically represents the point of variant formation. Hence, focusing on its processes is necessary when designing a strategy to increase the production flexibility (Petersen 2005). In addition, current developments (e.g. demographic changes and migration) imply that employers will have to deal with these additional diversities among their employees with respect to different performance levels in a short and long-term perspective. Therefore, there is a need for adaptable assembly systems, which tolerate interpersonal performance differences.

The final assembly of a manufacturer of white goods in Germany currently is organized as a typical clocked assembly system. The ability of the current concept to cope with the mentioned challenges is questionable. Therefore, the evaluation of alternative concepts for enabling long-term flexible and adaptable manufacturing is required (Latos et al. 2016; Latos et al. 2017).

The assembly organizational form of One-Piece-Flow can be regarded as an extended flow-line approach where the working person and the product exhibit concurrent movement characteristics. The assembly object is transferred along the assembly stations with either manual or electrically supported transportation equipment. The line is typically designed in a U-shape to minimize the walking distances for working persons. This principle implies that buffers within the line remain unnecessary, as working persons balance varying process times (Bullinger et al. 2009). In general, a single person is responsible for the complete assembly of a product, which represents a holistic product responsibility approach (Arzet 2005). The main advantages of such a system can be stated as enabling the assembly of diverse product variants. Moreover, a flexible output of the system can be achieved by adjusting the number of working persons in the system (Lotter and Wiendahl 2012; Schlick et al. 2010).

In this paper, the development of a One-Piece-Flow assembly simulation model in the field of the German manufacturer of white goods, which was conducted as participative innovation process, is presented. The assembly line is modeled with Colored Petri Nets. The model is implemented in FlexSim simulation software. In the following, simulation approaches are briefly explained and Petri Nets are introduced as well as the selected approach and the assumptions which have been used for modeling are presented. In the simulation analysis chapter and conclusion, the simulation results and their interpretation which can be used for decision-making are discussed.

ASSEMBLY SIMULATION APPROACHES

According to German VDI 3633 simulation is a method for reproducing a system in an experimental model in order to gain findings that can be transferred to reality (VDI3633). In general, simulation approaches can be classified as activity-oriented or actor-oriented (Duckwitz et al. 2010; Tackenberg et al. 2010). Actor-oriented approaches focus on the personnel's abilities and decision-making processes, whereas in activity-oriented approaches processes are driven by tasks. Both approaches can further be divided according to the degree of persons' consideration in the model (Duckwitz et al. 2010; Licht et al. 2007).

When considering different assembly concepts, one may regard monetary, capacity-related and flexibility-oriented decision criteria (Lotter and Wiendahl 2012). Nevertheless, it is crucial to follow a systematic assembly planning method for being able to reach a substantial decision. First, different assembly concepts can be developed. Next, a model can be developed for capturing the characteristics of the assembly concept. After that, simulation can be implemented and verified and finally, after validating the simulation results, the decision-making process follows (Banks 1998).

In order to model the process flow of an assembly line as a discrete event system Petri Nets were used. Petri Nets can be considered as a method that manipulates events according to certain rules. The great feature of Petri Nets is including explicit conditions that enable to model complex control schemes. A Timed Petri Net is a six-tuple (P, T, A, w, x, V) where (Cassandras & Lafortune 2008):

- P is the finite set of places (round nodes in the graph).
- T is the finite set of transitions (rectangular nodes in the graph).
- $A \subseteq (P \times T) \cup (T \times P)$ is the set of arcs from places to transitions and vice versa in the graph.
- $w: A \rightarrow \{1, 2, 3,...\}$ is the weight function on the arcs.
- x is a marking of the set of places.
- $V = \{v_j : t_j \in TD\}$ is the clock structure.

We can model deterministic or stochastic systems by relating the values of V to a set of known values and outcome values of a probability distribution function respectively (Cassandras & Lafortune, 2008).

Colored Petri Nets surpass the drawbacks of simple Petri Nets such as modeling the characteristics of the semi-finished products without adding another structure to the net and by giving attributes to tokens. Colored Petri Nets enable the analysis of temporal structures of manufacturing processes. Moreover, complex processes can be modeled with a high level of clarification which provides the opportunity for visual analysis. By adding another tuple "C" to the Petri Net, the Colored Petri Net can be defined where C is a non-empty set of colors and CS is a set of all color tokens that can be stored in a place S (Viswanadham & Narahari, 1987). Colors of token represent their attributes. Attributes represent data types, show characteristics of semi-finished parts, indicate process related properties of tokens or simplify the visualization of complex processes by differentiating between tokens (Jensen & Kristensen, 2015).

Model Conception

Here a washing machine was considered as a product with available variants for simulating its assembly process in a One-Piece-Flow assembly line. The modelling, simulation and evaluation was conducted according to the simulation procedures of Banks (1998). The processing logic of the simulation is stochastically modeled with Timed and Colored Petri Nets. Basic assumptions for modeling the process flow with a Petri Net were:

- Only one person at a time can work at one working station.
- Overtaking maneuvers should be possible during assembly. The model applies a performance index for each person that allows initiating overtaking procedures. If a person arrives at a working station where another person with a lower performance index is already assembling, the assembling person will finish the task, then wait and let the latter to overtake.
- There is no shortage in assembled materials.
- For each task, the simulation uses proper task execution times. As real assembly times are distributed, a Gaussian distribution of the assembly times is implemented in the model. In addition, other distributions can be applied.

Ultimately, the simulation model calculates the assembly times as follows in equation (1):

$$t_{ij} = OEI_j * SEI_{ij} * t_i \sim N(\mu_i, \sigma_i^2) \qquad (1)$$

t_{ij} = assembly time for employee j at work station i
OEI_j = overall efficiency index of employee j
SEI_{ij} = stationwise efficiency index of employee j at station i
μ_i = standard time at station i from working plan
σ_i^2 = standard deviation of standard time at station i

The simulation model is based upon the two-dimensional block layout of the assembly line which was created by using an open access factory planning PowerPoint tool (Kampker et al. 2012). The model defines stopping points within the layout and imports the corresponding MTM-UAS standard times from a database. This allows for simulating the assembly of different product variants. Moreover, variants that happen to not require one process step feature a standard time of zero for that specific process. This enables the simulation of mixed model production programs.

Unrealistic accumulations of working persons in spatially close areas can be avoided by assigning a maximum number of tolerable persons for certain areas of the assembly line.

The activities of a workstation including overtaking maneuvers as a subsystem are modeled with Timed Petri Nets. The Colored Petri Net is used to facilitate visual analyses of the system, as suggested by Gradisar & Music (2013). The Petri Net graph is shown in Figure 1.

The Petri Net model then was hard coded in FlexSim 2017 in a process flow. Features of the software were used to create a 3D model (Figure 2) and integrate the process flow into it. The model allows to set different parameters for each simulation run. To do so, input variables like the number of persons, traveling speed, performance indices and starting positions of persons as well as shift duration were defined to simulate different scenarios. In addition, the model incorporates fixed inputs and disturbance variables.

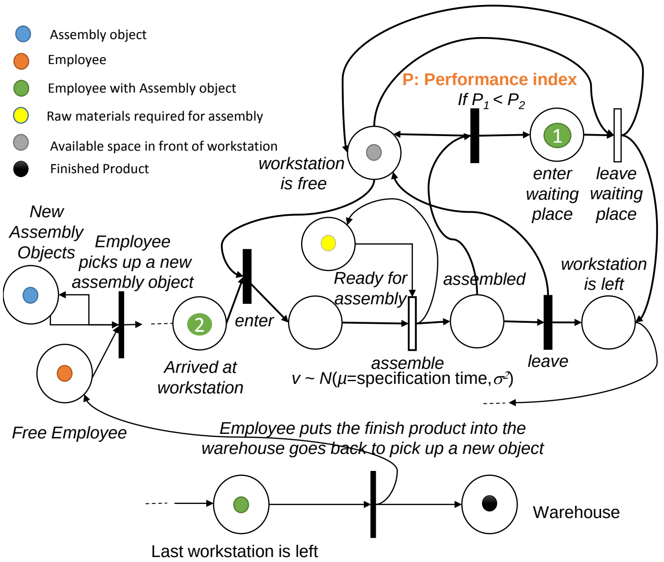

Figure 1: Colored Petri Net model of the assembly line

Figure 2: 3D simulation model in FlexSim

For verification, validation and testing techniques informal, static as well as dynamic methods described by Banks (1998) were employed. For instance, an expert evaluation was used as informal approach, whereas a semantic analysis of the source code was conducted as static method. As a dynamic technique, sensitivity analyses were performed with respect to the parametrization of the model.

SIMULATION ANALYSIS RESULTS

The system behavior of the assembly line can be explored, as the input variables can be varied within multiple simulation runs. However, this paper only presents a range of simulation results. Moreover, the data has been modified by applying a fictitious multiplication factor to the results by means of industrial data protection.

In theory, normalized cycle time is calculated by dividing the overall work content by the number of persons in a One-Piece-Flow system (Arzet 2005). This determines the output of the system. By varying the normalized cycle time, one can meet the actual cycle time, which is induced by customer demands.

Yet, it is trivial to understand that the output of the system will not increase proportionally if one increased the number of workers incrementally. In fact, the normalized output time cannot be reduced to a minimum because no arbitrary high number of employees can be assigned to a One-Piece-Flow system. Therefore, the output also will flatten at some point.

With simulation it is possible to determine the number of workers in the system from which on the output does not continue to grow proportionally without the physical existence of the assembly line.

Therefore, the number of employees in the line was gradually increased and (n = 200) simulation runs were conducted for every scenario. The output of the system was tracked in order to determine the point from which on the output flattens because of the increase in waiting times due to interpersonal disturbances (Figure 3). By doing so, statistical conclusions concerning the output can be drawn. For instance, confidence intervals for the output regarding a certain assembly scenario can be calculated.

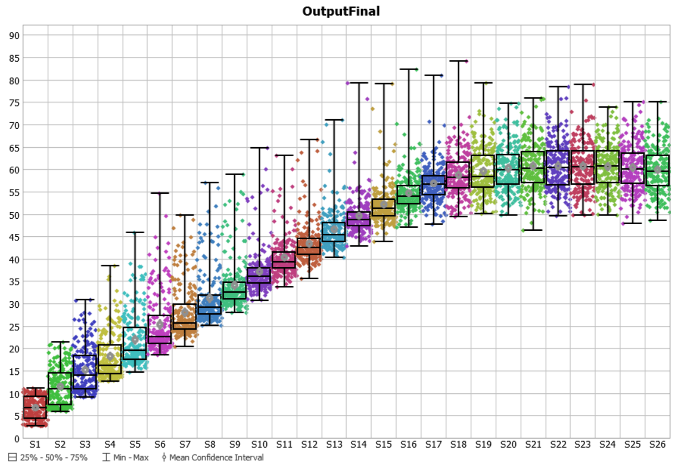

Figure 3: Exploration of possible outputs with respect to the number of persons in the assembly line (modified data, simulation analysis conducted with FlexSim)

The simulation approach enables the consideration of capacity-examinations in an early planning phase. This supports the decision process when comparing different assembly concepts. Furthermore, the employees' ratio of different activities or the composition of throughput times can be tracked and analyzed. Simulation may help to iteratively approximate towards the ideal operating point of a production system. This facilitates to launch the system in a more efficient manner.

Evaluation Of Assembly Time Distribution Types

Fischer et al. (2005) state that an important consideration during the design and simulation phase of an industrial assembly station should be the stochastic nature of assembly times. Therefore, the question to be answered is which type of distribution should be used (Fischer et al. 2005). Possible types of continuous distributions, which can be applied in simulation, are presented in (Banks 1998). Fischer et al. (2005) state that the problem during a data collection phase of a simulation project is that the required parameters for the often-suggested Normal- or Gamma-distribution are usually not available. In contrast, the parameters of the beta distribution were easy to estimate, since they are characterized by an optimistic, pessimistic and a most common time value (Fischer et al. 2005; Schlick and Demissie 2015). Neumann (1975) recommends choosing a distribution for execution times that fulfils three conditions:

Firstly, the distribution should be steady; secondly, the resultant activity execution times should be bounded above and below, and thirdly, the realization of activity execution times should be concentrated around a certain value. Fischer et al. (2005) conclude that the beta distribution complies with these conditions and possesses the additional advantage of modelling stochastic activity times with the PERT methodology by using an easy accessible estimation of an optimistic value (OT), a pessimistic value (PT) and a most common value (see Figure 4 and also Neumann 1987). Furthermore, the parametrization of shaping parameters enables to model non-axially symmetric execution times (Banks 1998). Finally, Krajewski and Ritzman (1999) also suggest that this approach is suitable for modelling strongly scattered operation durations (see also Fischer et al. 2005).

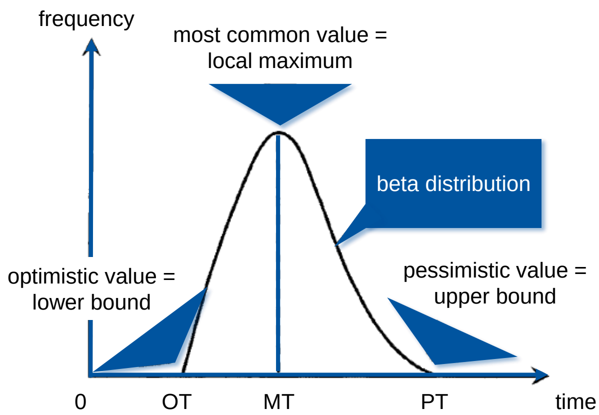

Figure 4: Modelling beta distributions according to the PERT methodology (in the style of Fischer et al. 2008)

For modelling assembly times in this simulation approach, a parametrization of beta distribution was chosen which has a longer tail to the right side since assembly times will rather tend to take longer due to disturbances. The symmetric normal distribution has the drawback that a situation where an employee assembles faster than standard time has the same probability as a situation where he needs longer within a certain absolute value of standard deviation above and below the mean. Hence, the beta distribution was parametrized in FlexSim in the following way:

$$t_i = beta(0.75 * \mu_i, 2.00 * \mu_i, 2, 5, default) \qquad (6)$$

μ_i = standard time at station *i* from working plan

In order to analyze whether beta distributed assembly times do effectively affect the simulation results, a comparative study was conducted and the testing hypothesis were formulated as follows:

H_0: **There is no difference between the mean values of normal and beta distributed assembly times.**

H_a: **There is a difference between the mean values of normal and beta distributed assembly times.**

In this paper, exemplary results for the saturation point of the assembly system with respect to the number of employees working in it are presented. On the one hand normally distributed assembly times were assumed and (n = 200) simulation runs were conducted. This procedure was repeated with the assumption of beta-distributed assembly times according to equation (6) on the other hand. Figure 5 illustrates the results as total output per shift.

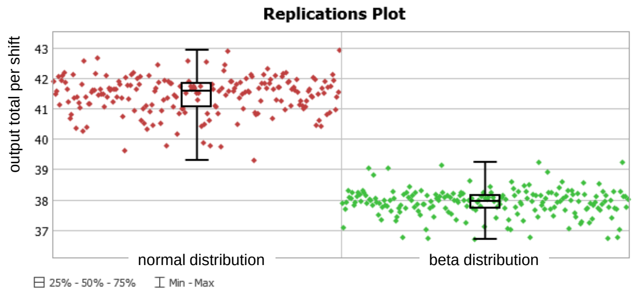

Figure 5: Comparison of normal and beta distributed assembly times (modified data, simulation analysis conducted with FlexSim)

From Figure 5 a significant difference between the two distribution times may be expected. This can be shown by means of statistical testing methods. A selection of a suitable method was conducted according to the approach of Albers et al. (2009). Due to the consideration of one variable and the level of measurement, a parametrical test of two independent samples was conducted as a two-sided t-test.
The calculated p-value ($p < 0.0001$) is smaller than the chosen significance alpha level of 0.05, thus the null hypothesis H_0 must be rejected, whereas the alternative hypothesis H_a should be accepted. The risk of rejecting H_0, even though it may be true, is less than 0.01 %. In conclusion, the application of beta distributed assembly times and the chosen parametrization in the simulation does affect the simulation results in terms of lower output values. Hence, it is important to further evaluate in field studies which distribution type describes assembly times in a One-Piece-Flow system more accurately.

CONCLUSION

This paper presents the approach of simulating a One-Piece-Flow assembly line at a manufacturer of white goods in Germany in an early planning phase. The simulation helps to predict the system's behavior and enables capacity-examinations without its physical existence.
It was shown that the chosen parametrization of beta parametrization leads to a lower system output in comparison to the parametrization of assembly times as a normal distribution.
The simulation model makes it possible to examine diverse questions in an early planning phase. Moreover, the model can be used in further planning steps to predict the system's behavior with an updated data basis in a more accurate way. However, one must consider that simulation cannot model human interactions adequately. Especially psychological influences on working persons are not explicitly modelled. By employing variances in simulation, uncertainties can at least be considered. In the end, the results are based on assumptions that can be discussed controversially.

FUTURE RESEARCH

Simulation enables to apply distributions of process times; hence, results that are more realistic can be achieved in comparison to calculations which employ fixed standard times. However, further research should evaluate whether a beta distribution approximates assembly times in a One-Piece-Flow system more accurately than a normal distribution. This may be achieved with time studies for such assembly systems.

Finally, it is possible to parametrize and validate the model more precisely with empirical values after implementing the assembly line. In this regard, the simulation results may also be practically validated as well as a simulation tool can be used as an operative planning tool to forecast the output before shift start. If an automated tracking system was implemented, the production manager could simultaneously track the position of the product and therefore display the assembly progress within the simulation model in real-time. With regard to the field of industry 4.0, the assembly status would always be accessible, transparent and even predictable. Future research will focus on different working modes of a One-Piece-Flow system, as it can also be run whist dividing the overall work content into segments that are assigned to different employees respectively. Moreover, it is possible to evaluate whether these segments should be assigned to working groups that may support each other in terms of cooperative work when a group happens to have lots of products in the waiting queue of their line segment. Simulation will further be explored as a method for designing work systems in a participative way. In this context, virtual reality (VR) technology can be used to directly visualize planning results of workshops with employees in a VR-environment. Ergonomic assessment methods will be integrated into the simulation model in order to analyze the ergonomic implications for working persons in an early planning phase. Furthermore, web based simulation approaches will be evaluated to enable small and medium-size companies to tackle the digital transformation of their planning processes.

ACKNOWLEDGEMENT

The foundation of this case study concerning the composition of diverse innovation teams was developed within the research project “derobino” (2011-2015) funded by the Federal Ministry of Education and Research in Germany according to Grant No. 01HH11007. The authors would like to express their gratitude for this support.

REFERENCES

Albers, S.; Klapper, D.; Konradt, U.; Walter, A.; Wolf, J. 2009. Methodology of Empirical Research (in German). 3rd ed.. Wiesbaden: Gabler

Arzet, H.: Grundlagen des One-piece-flow. 2005. Guideline for planning and realizing operator-based production systems (in German). Berlin: Rhombos.

Banks, J. 1998. Handbook of Simulation. Principles, Methodology, Advances, Applications and Practice. New York: Wiley.

Bullinger, H.; Spath, D.; Warnecke, H.; Westkämper, E. 2009. Handbook of Enterprise Organization. Strategies, Planning, Implementation (in German). 3rd ed.. Berlin: Springer

Cassandras, C. G., & Lafortune, S. 2008. Introduction to Discrete Event Systems. 2nd ed.. Springer.

Duckwitz, S.; Tackenberg, S.; Karahancer, S.; Schlick, C. M. 2010. A Meta-Model for Actor-Oriented, Person-Centered Simulation for the Management of Development Projects. *In: Proceedings of the 17Th International Conference on Industrial Engineering and Engineering Management*

Fischer J., Stock P., Zülch G. 2005. Simulation of Disassembly and Re-assembly Processes with Beta-distributed operation Times. In: Zülch G., Jagdev H.S., Stock P. (eds) Integrating Human Aspects in Production Management. IFIP International Conference for Information Processing, vol. 160. Springer, Boston, MA

Gradisar, D., Music, G. 2013. Petri Net modelling for batch production. 7th IFAC Conference on Manufacturing Modelling, Management. Saint Petersburg. 1566-1571.

Jensen, K., & Kristensen, L. 2015. Colored Petri nets: a graphical language for formal modeling and validation of concurrent systems. Communications of the ACM, Vol. 58. No. 6, 61-70.

Kampker, A.; Burggräf, P.; Mecklenborg, A.; Kreisköther, K. 2012. Efficient Layout Planning in Interdisciplinary Teams. Complexity-suiting Tools Enable Sustainable Project Success (in German). In: VDI-Z. 154. Vol. 2012, No. 11/12, 74-75

Krajewski, L. J.; Ritzman, L. P. 1999 Operations Management. Reading, MA.: Addison Wesley.

Latos B. A., Holtkötter C., Brinkjans J., Mütze-Niewöhner S. 2016. Simulationsbasiertes Vorgehen zur Planung einer Montagelinie nach dem Prinzip One-Piece-Flow (in German). IAW Spectrum, Vol. 12, 8-9.

Latos B. A., Holtkötter C., Brinkjans J., Przybysz, P. M., Mütze-Niewöhner S., Schlick C. M. Partizipatives und simulationsgestütztes Vorgehen zur Konzeption einer flexiblen und demografierobusten Montagelinie bei einem Hersteller von weißer Ware (in German). *In Proceedings of 63. Kongress der Gesellschaft für Arbeitswissenschaft : FHNW Brugg-Windisch*, Switzerland, 15.-17. February 2017

Licht, T.; Schmidt, L.; Schlick, C.; Dohmen, L.; Luczak, H. 2007. Person-centred simulation of product development processes. In: Int. J. Simulation and Process Modelling, Vol. 3, No. 4, 204-218

Lotter, B.; Wiendahl, H.-P. 2012. Assembly within Industrial Production. A Handbook for practitioniers (in German). 2nd ed.. Berlin: Springer

Neumann, K.: Operations Research Verfahren. Vol. 3: Graph Theory, Network Analysis (in German). Munich, Vienna: Carl Hanser Verlag, 1975.

Neumann, K. 1987. Network Analysis. In: Fundamentals of Operations Research, part 2. (in German). ed.: GAL, Tomas. Berlin et al.: Springer, 165-260.

Petersen, T. 2005. Forms of Organization in Assembly. Theoretical Foundations, Organizational Principles and Configuration Approaches (in German). Aachen: Shaker

Schlick, C.; Bruder, R.; Luczak, H. 2010. Industrial Engineering (in German). 3rd ed.. Berlin: Springer

Schlick, M.; Demissie, B. 2015. Product Development Projekcts. Dynamics and Emergent Complexity. Heidelberg: Springer

Spath, D.; Müller, R.; Reinhart, G. 2013. Future Assembly Systems. Economic, Changeable and Reconfigurable (in German). Stuttgart: Fraunhofer

Tackenberg, S.; Duckwitz, S.; Schlick, C. 2010. Activity- and actor-oriented simulation approach for the management of development projects, In: International Journal of Computer Aided Engineering and Technology, Vol. 2 No. 4, 414-435

VDI-Richtlinie 3633. Simulation of Logistic-, Material Flow- and Production Systems, Foundations (in German). VDI-Handbuch Materialfluss und Fördertechnik, Band 8. Berlin: Beuth Verlag.

Viswanadham, N., & Narahari, Y. 1987. Colored Petri net models for automated manufacturing systems. In Proceedings of IEEE International Conference on Robotics and Automation, Raleigh, NC, 1985-1990.

WEB REFERENCES

FlexSim Software Products, Inc. (FSP). 2017. FlexSim 2017 manual, URL: https://www.flexsim.com/