Simulating Wood-framing Wall Panel's Production with Timed Coloured Petri Nets

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Abstract –

The integration of design and construction processes remains, after decades of dedicated research, a great challenge. Even considering the specific context of pre-fabrication and modularization, it was just in recent years, with increasing adoption of Building Information Modeling (BIM) processes, that the challenge, albeit in a virtual environment, begins to be really addressed. With the advent of the Digitization phenomena in Construction, and the advances in Machine Learning techniques to cope with uncertainties of different natures in modelling real processes, it seems that the use of computational tools to simulate off-site production should be reconsidered. In this article, it is adopted an approach in viewing BIM as in a development stage to become an implementation of Product Lifecycle Management (PLM) for Construction. Towards this end, it is identified the lack of representation of the entire dynamics of production processes inside BIM models. The proposition of using Petri Nets with stochastic transitions to represent and simulate those processes are presented, altogether with the use of real RFID data, to adjust the model parameters, collected from a case study with a Brazilian company that pre-fabricate wood-framing houses. The probability distributions are derived based on the Mixture of Gaussians algorithm, and considers parameters of the design of wall panels – so it could be used to extrapolated performance for new designs. Following the presented approach, it is expected that, with more data, the simulation process could be a good feedback to architects in evaluating the impact of its design options in production.

Keywords –

High-level Petri Nets; Building Information Modeling; Simulation; Wood-framing

1 Introduction

In general, architects are not able to exploit design choices and its impact in production processes: they would need to specialize in each existent building system. Design is just one phase of the product development lifecycle, and through it, it will need the expertise of many different professionals. As communication between them is normally scarce and noisy, many opportunities to produce a better product is lost, and problems found later, on construction phase, could be traced back to unaided design decisions.

Computational tools have been developed to aid in this context, but there are still problems, and limitations. Even with the growing importance of information and communication technologies, the integration of design and construction processes remains, after decades of dedicated research [1], a great challenge. The situation is not different when one considers the specific context of pre-fabrication and modularization. It should be expected that in industrialized construction, similar to manufacturing industries, the use of computer-aided systems would be more common. It was just in recent years, with increasing adoption of Building Information Modeling (BIM) processes, that the challenge of integrate the processes of design and construction, albeit in a virtual environment, begins to be really addressed. And because of it, the interest in using pre-fabrication and modularization is rising again [2].

In viewing BIM as in a development stage to become an implementation of Product Lifecycle Management (PLM) for Construction [3], BIM models should resemble the idea of a digital twin, where it is possible to trade working with bits instead of atoms [4]. To use it to give to architects an advanced feedback of the impacts of planned design in production, it would be necessary to build a simulation of the production process in the factory. Although largely employed in other industries, for Construction, simulation have had more success in academic research than large use by the industry [5]. It is natural that with the advent of the Digitization phenomena in Construction, and the advances in Machine Learning techniques to cope with uncertainties of different natures in modelling real processes, it seems that the use of computational tools to simulate off-site production should enter a new cycle of development [5], and integrate with digital information provided by BIM models.

BIM models are Product Data Models, and lacks the representation of the processes [6]. As so, there is a lack of representation of the entire dynamics of production processes inside BIM models – it is possible to create information about sequential tasks in the model; however, there is few semantic contents to that representation. As an illustration, consider IFC (Industry Foundation Classes) schema for interoperability. There is a growing presence of physical building components in the information model. However, although one could create, from basic entities, and describe construction processes, there will not be an inherent semantic in the representation. There isn't a library of processes to be used "off-the-shelf".

In this article, the proposition of using Petri Nets with timed coloured extension to represent and simulate those processes is presented, altogether with a procedure to use RFID data to adjust the model parameters. Implementation and test were done in a case study with a Brazilian company, which pre-fabricate wood-framing houses. Time representation in a coloured Petri Net is done via delays imposed to each transition. The delays are statistical, based on probability distributions. The probability distributions are derived based on the Mixture of Gaussians algorithm, and considers parameters of the design of wall panels – so it could be used to extrapolated new designs. Each type of wall panel contributes with a normal distribution, which composes the mixture distribution.

In section 2, we briefly present the mathematical formulation of Petri Nets, with extensions for time and colours (tokens are from different kinds in the simulation). Section 3 presents a proposition to derive parameters for mixture of gaussian model of the probability distribution to use in the delay of the Petri Nets. Section 4 presents the experiment that were done with the simulation of the production of wall panels in wood-framing, in a Brazilian company. And finally, section 5 summarizes the presented work, drawing some conclusions about our approach, and indicates future direction of work.

2 Petri Nets for Construction Processes Simulation

The main view about the formalism of what late became known as Petri Nets, and its potential as a model for dynamic systems was conceived in the PhD thesis of Carl Adam Petri [7].

Research in the use of Petri Nets to model asynchronous and concurrent dynamic systems, such as manufacturing systems started to appear in the scientific literature around the 80's. However, for the application of Petri Nets to real world problems, it was necessary to develop many high-level extensions of the traditional Petri Net formalism; for example, to include time, and a way to represent different kind of tokens (coloured).

2.1 Timed Coloured Petri Nets

The concept of Coloured Petri Nets was proposed by Jensen [8], as an high-level Petri Net. Following definition of Viswanadham and Narahari [9], a Coloured Petri Net is defined by the quintuple:

$$N = (P, T, C, I, O) \quad (1)$$

$$P = \{p_1, p_2, p_3, \dots, p_n\}, n > 0 \quad (2)$$

$$T = \{t_1, t_2, t_3, \dots, t_m\}, m > 0 \quad (3)$$

where: P is a finite set of places; T is finite set of transitions; such that $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$.

$C(p)$ and $C(t)$ are the set of colours associated with place $p \varepsilon P$ and $t \varepsilon T$.

$$C(p_i) = \left\{a_{i1}, a_{i2}, \dots, a_{iu_i}\right\}, i = 1,2,\dots,n \ and\ u_i = |C(p_i)| \quad (4)$$

$$C(t_j) = \left\{b_{j1}, b_{j2}, \dots, b_{jv_j}\right\}, j = 1,2,\dots,m \ and\ v_j = \left|C(t_j)\right| \quad (5)$$

$I(p,t)\colon C(p) \times C(t) \rightarrow \mathbb{N}$ is an input function and $O(p,t)\colon C(p) \times C(t) \rightarrow \mathbb{N}$ is an output function.

There is also a token, a mark inside places, to represent the dynamics of the net. One transitions only occurs if there are token in every place connected to it (input set). And if a place is connected to two transitions, and both could fire, a decision should be made.

The concept of time in Coloured Petri Nets (although it could also be inserted in classic Petri Nets) has been implemented as a delay in turning available the tokens generated by a transition. Also, it is possible to employ probability distributions to model uncertainty and randomness in the time of completion of each task.

3 Learning Probability Distributions with Mixture of Gaussians

As there is the necessity to expose some parameters of the model to represent different panel designs, it was chosen to represent the probability distribution as an mixture of Gaussians, in which each Gaussian is attributed to one already monitored production of panel design.

It is expected that, with monitoring many different projects, from houses to buildings, this mixture of Gaussians could capture the intricacies and particularities of products in a company's production line and be extrapolated to new designs. Then, it could be a source of feedback to the architect based on simulation results, and optimization.

Figure 1 represents graphically how two gaussian distributions could be used to model a multimodal histogram. It is expected that each individual wall panel design would give a specific normal distribution, and that with a large database of production of different designs, for houses and buildings, it should be relevant to predict, based on the estimated mixture of gaussians, future time delays for unseen product design.

The representation of a probability distribution using a mixture of Gaussians as a model, following Figueiredo and Jain [10], is given by:

$$p(y|\theta) = \sum_{m=1}^{k} \alpha_m p(y|\theta_m) \quad (3)$$

$$\alpha_m \geq 0, m = 1, \dots, k, and \sum_{m=1}^{k} \alpha_m = 1 \quad (4)$$

$\theta_m$are the parameters of the model to be find based on data collected.

Traditionally, it is used Expectation-Maximization algorithm to obtain the values of θ, with the formulation presented in (5):

$$\begin{aligned} \log p(\Upsilon|\theta) &= \log \prod_{i=1}^{n} p\left(y^{(i)}|\theta\right) \\ &= \sum_{i=1}^{n} \log \sum_{m=1}^{k} \alpha_m p\left(y^{(i)}|\theta_m\right) \end{aligned} \quad (5)$$

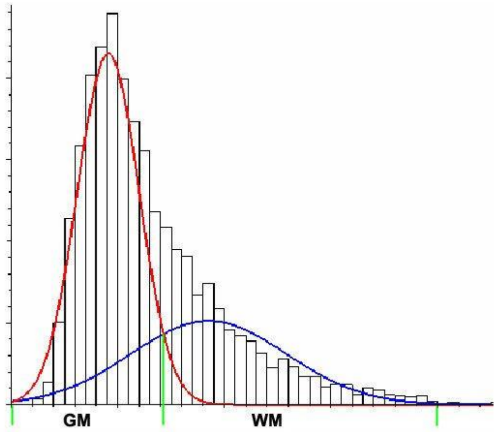

Figure 1. Representation of gaussians distributions derived from a histogram data.

4 Experiments and Results

In the last section, it was demonstrated how to obtain a probability distribution, based on data collected from real process. In our experiments, we do not achieve yet a relevant amount of data to use this methodology. The amount of data acquired is not statistically relevant but was adequate to obtain some estimation of the duration of each activity in the wall panel production, and to test the Petri Nets, and the model of a Mixture of Gaussian probabilistic distribution, as valid representations or models to use in our objective to provide a feedback of the impacts in design of alternative design decisions.

4.1 Production process at a Brazilian company of prefabricated homes in wood-framing

Production plant layout is represented in Figure 2. There are 6 working stations (identified by blue rectangles in the figure and labelled with numbers in white). The numbers represent the processing order.

Their plant is organized as a production line, without buffers. This is known in the factory as “Weinmann line”, after the Weinmann machinery bought by the company, which produces only wall panels. Floor and roof panels are produced manually, and in parallel lines (and are not represented in the figure).

The frame of each panel is composed of studs that are gathered from storage magazines (red rectangle, with an **S** in it), and from special modules (for door and window installation), which are also produced manually in another workstation.

There is a framing machine that reads the digital model and fix one component in the other, until the frame is finished – the red rectangle with the **SA** letters indicate where there is the storage and the other machine that automatically feeds the internal studs to the framing machine.

Workers bring OSB boards from storage (red rectangle with **OSB** in it) and position them with preliminary use of nails. There is another machine that cut electric and hydraulic openings in the OSB board, in both workstations 2 and 4 – represented by a blue rectangle, and a **W** letter in white for the representation of the machine itself.

Transportation between work station 2 and 3 is done by a “butterfly” table mechanism (Figure 3), allowing to work in the other side of the frame, to close it. Work station 4 is movable.

In the workstation 5, two to three workers install Tyvek film in the panel, insert the frame for windows and doors installing (the local where these frames are is represented by the red rectangle with the E letter in it), and put plasterboard – storage of plasterboard are represented by the red rectangle with the **G** letter in it. This work is also carried out in the workstation 6, so they have more space to complete these tasks in two panels.

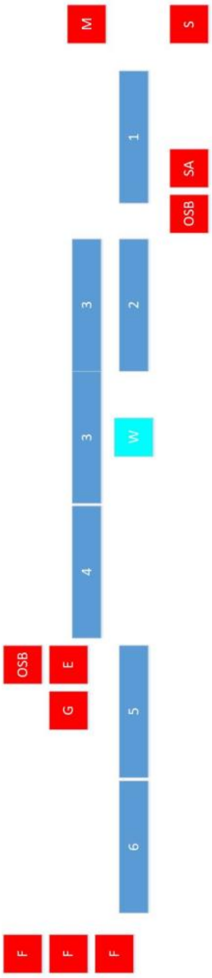

Figure 2. Rough layout of the production plant – not necessarily on scale.

Figure 3. One of the workstations ("butterfly" table) at the production plant.

After completion, the panel is moved by a crane, to temporary storage – represented by three red rectangles with the **F** letter in it.

4.2 RFID Data Collection

As stated by Mullens [11], "[q]uantitative data measuring cycle time variation and its root causes are rarely available". It is important to develop some solution to automatically capture such data. One solution could be an RFID system.

The RFID system employed to temporarily collect data at a Brazilian company was composed by three Sargas Readers from Trimble, and three antennas of 9 Db (one for each reader, although each reader could be used to gather data from two antennas – Figure 4). The maximum workable range between antenna and passive tags were estimated in 1.2 m.

Each panel received two tags, one in each of its lateral studs. The three points of time measure was: 1) immediately after the framing machine (the use of the frame machine is known by the log of the machine); 2) immediately when the panel, turned around, goes back to the main line of production; 3) Between work done in workstations 5 and 6, until the finished panel is elevated to the storage area.

Figure 4. One of the RFID Antennas temporarily installed for data collection in the factory of a Brazilian company.

During two days of collecting production data, it was possible to acquire some information about the dynamics of production for the line in general, and for each panel. However, such amount of data do not have statistic relevance to be used in estimating a global parameter for probability distribution.

It was decided to just attribute some values, compatible with data collect, to investigate if the proposed solution, Petri Net formalism, given relevant data, could be used as original planned.

4.3 Petri Net Model of Production Line

To build a model representation of the production line of wall panels in wood-framing for the prefabrication of homes in Timed Coloured Petri Net, and to analyze its performance, it was used the software CPN Tools [12].

The resources needed for each activity were modeled by places. There were places for workers, machines, and panels along the production process. A mark in a place means that the resource is available.

The coloured sets extensions allows modelling of different panel designs (they were formatted as coloured sets of the product of an INT – order of production – and a STRING – type of each panel), and the modelling of distinct resources, such as workers and machines (defined as INT).

With the timed extension allowed, every activity in the production line was modelled with time delayed transitions, with a probability distribution composed of a mixture of gaussians. Each arc leaving a transition received a delay of a weighted sum of normal distributions such as (we opted to use only two types of gaussian to simplify, as the extension to the five different wall panels to assemble a house is straightforward):

$$F(x) = \sum_{i=1}^{5} 0.2 * normal(n_i, v_i^2) \quad (6)$$

Places representing the stages of wall panel production demanded a special treatment because an upcoming place should be empty before a previous transition is enabled – so that it not accumulate two panels in the same workstation. As a general and needed solution for this model, it was necessary to create for each pair of consecutive transitions representing work done at workstations, two additional places to avoid accumulation of more than one token in each place – that represents the panels in the workstations (Figure 5). This solution also helped in controlling the sequence of different panels to be produced.

There are 10 activities represented that were already described in previous section (we also give here the average time delays for the two gaussians employed in the simulation):

1. Frame production (time delay: 10 / 11 min);
2. OSB-one side (time delay: 7 / 6 min);
3. Cutting (time delay: 4 / 3 min);
4. Butterfly use (time delay: 4 / 3 min);
5. Electric, HVAC, Cutting, and OSB (time delay: 7 / 6 min);
6. Back to main line (time delay: 3 / 2 min);
7. Cutting-other side (time delay: 4 / 2 min);
8. Door and Windows install, Tyvek (time delay: 32 / 30 min);
9. Plaster board (time delay: 20 / 18 min);
10. To storage (time delay: 6 / 5 min);

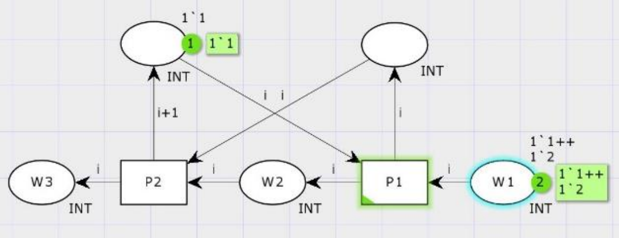

Figure 5. Modelling order of and workstation capability of production.

Figure 6 shows details of the modelling of shared resources in some workstations / activities – the model reproduces the same logic of the layout presented previously: the cutting machine receives a digital design, and it cuts small holes for electric and hydraulic use, and also there is in general one single operator to coordinate movement of wall panels and the machine that do the cutting in two different workstations – in the network. In red are highlighted two workstations (places) where cut, in both faces of the wall panel, occurs and in blue are highlighted two resources (places), operator and machine, that are divided between the workstations.

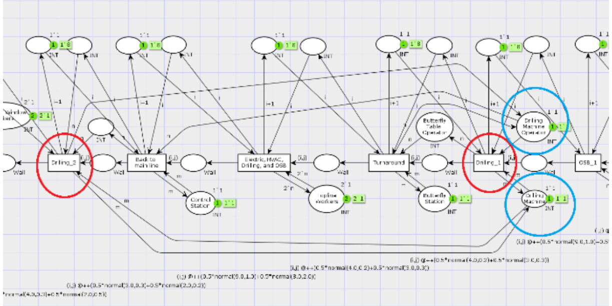

Figure 6. Detail of resources (Drilling Machine and Operator) between different workstations.

Due to the large network obtained, and the lack of space in the article, we opted to give an overview of the topology of the Petri Net, without giving more details (Figure 7).

The bottleneck of the production process is known to be work in the fifth and sixth stations, which is entirely manual, and there are a lot of work to do in it.

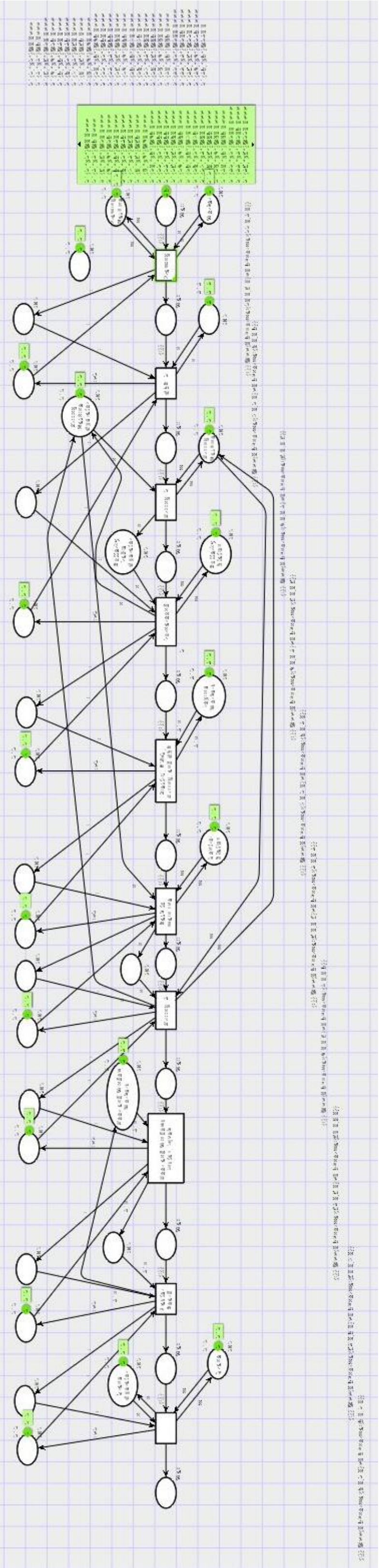

Figure 7. Timed Petri Net representing production of wall panels.

Part of the real dynamics that was not modelled was the movement of workers along different workstations to help its colleagues to keep in the TAKT time. For this, it would be necessary to model agents with decisions, and rewards.

As one example where it happens and is relevant for the dynamics, there is such a case just after the first transition with the operator of the framing machine. He works by itself until the frame is finished. The frame then moves to the next work station, and he also starts to work along two other workers, in fixing OSB boards on the frame. Based on a timed-schedule, he decides when to start a new wall panel, going back to operate the framing machine.

4.4 Results

Our experiment was developed to investigate the Timed Coloured Petri Net, as a formalism, and CPN Tools, as an implementation software, to produce a discrete-event simulation model of the production process. As a result, we could model almost every feature that appears to be relevant to our intent.

However, one behaviour would be of interest, although until the present knowledge of the authors, it is impossible to model it explicitly or directly with Petri Nets: variable time of transitions based on the number of tokens in a place representing resources, i.e., in some occasions, two to three workers are in a specific workstation, and the amount of time to complete the job depends on the size of the workforce at that moment.

The network was simulated with a production programming of 25 wall panels, in two different scenarios. In each scenario, the time delay between the beginning of production process of new panels was delayed by 5 and 10 minutes, respectively.

Table 1. Probability distribution parameters.

	1st Gaussian	2nd Gaussian
Place 1	26 ± 3	20 ± 2
Place 2	9 ± 1	7 ± 0.5
Place 3	4 ± 0.2	3 ± 0.3
Place 4		
Place 5	9 ± 1	8 ± 2
Place 6	3 ± 0.3	2 ± 0.2
Place 7	4 ± 0.3	2 ± 0.5
Place 8	40 ± 3	29 ± 8
Place 9	40 ± 5	38 ± 7
Place 10	6 ± 1	5 ± 1

The production time of each panel throughout the experiment (Table 2) was around the same time obtained in monitoring the production for two days at the plant. Results are exhibited in Table 2.

The registered times in Table 2 refer to the global clock of the simulation (that starts at zero with the beginning of production of the first wall panel), at the time that each panel is moved to temporary storage. For each scenario, we run the network 5 times, and calculated the average time and its standard deviation.

Table 2. Results from simulating the production plant for two scenarios. The timestamp at the end of the production line is exhibited in the columns.

Type of wall panel	Global clock (s)	
	Scenario 1 (Δ10min)	Scenario 2 (Δ20min)
Type 1	129.6 ± 3.5	130.0 ± 3.4
Type 2	167.2 ± 4.5	169.6 ± 3.2
Type 3	207.7 ± 4.5	208.1 ± 3.0
Type 4	246.4 ± 5.3	246.9 ± 3.3
Type 5	283.8 ± 4.6	286.4 ± 3.6
Type 1	323.1 ± 4.5	324.7 ± 3.8
Type 2	363.0 ± 7.9	363.1 ± 4.4

Verification and validation of results from simulation were done based on comparison with real data collected with RFID system. Even if the collected data is a scarce set, it was verified that the probability distribution applied to the model was able to reproduce compatible times with the observed practice. During the simulation of one entire day of production, 8 hours of work, the behaviour of the model was similar to what was observed in the factory. Thus, it is a promising implementation of a process simulation to be further developed, towards obtain a feedback to architect of design decision on production.

5 Conclusions

The aim of the research present in this paper, was to investigate an adequate formalism to make use of different simulation models that could integrate somehow with digital information provided by BIM models.

It was presented how to use a Timed Coloured Petri Net to represent the off-site production of wall panels for wood-framing houses. The focus was in the specific plant (and processes) of a Brazilian SME. It was also presented a methodology to derive probability distributions from real data of production times collected with RFID systems. However, in the experiment we used guessed values, based on data collected, due to not have collected a representative amount of data until now – two days of data collection, including installation of equipment, and trials with regard to the position of antennas in the factory and tags in the wall panels. Through simulation of the production process, it was possible to derive TAKT time to have a balanced production.

Future goal is to be able to predict production times for new design of wall panels, and thus, to be able to give feedback to architects during design decision making process. Also, it is our intent to install RFID system in the factory, and to automatically monitor the production for one or two months in the near future. We also need to further develop the simulation model, to include stoppage of machinery due to fault, and due to maintenance to obtain a more realistic simulation model.

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References

[1] Yamazaki, Y. Integrated design and construction planning system for Computer Integrated Construction. *Automation in Construction*, 1(1):21-26, 1992.

[2] McGraw-Hill Construction, Prefabrication and Modularization, 2011.

[3] Jupp, J. R. Cross industry learning: a comparative study of product lifecycle management and building information modelling. *International Journal of Product Lifecycle Management*, 9(3):258-284, 2016. doi:10.1504/IJPLM.2016.080502.

[4] Grieves, D.M. *Virtually Perfect - Driving both lean and innovative products through Product Lifecycle Management*, Space Coast Press, 2011.

[5] AbouRizk, S. Role of Simulation in Construction Engineering and Management. *Journal of Construction Engineering and Management*, 136(10):1140-1153, 2010.

[6] Pan, W. and Langosch, K. and Bock, T. Development of the Process Information Modelling in the Construction Project: A Case Study of the ZERO-PLUS Project. In *Proceedings of the International Symposium on Automation and Robotics in Construction*, Taipei, Taiwan, 2017.

[7] Silva, M. 50 years after the PhD thesis of Carl Adam Petri: A perspective. In *Proceedings of the IFAC Workshop on Discrete Event Systems*, Guadalajara, Mexico, pages 13–20, 2012.

[8] Jensen, K. Colored Petri-Nets and the Invariant Method, *Theoretical Computer Science*, 14(3):317-336, 1981.

[9] Viswanadham, N. and Narahari, Y. Coloured Petri net models for automated manufacturing systems. In *Proceedings of the 1987 IEEE International Conference on Robotics and Automation*, Raleigh, United States of America, pages 1985–1990, 1987.

[10] Figueiredo, M.A.T. and Jain, A.K. Unsupervised learning of finite mixture models. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24(3):381–396, 2002.
[11] M. Mullens, *Factory Design for Modular Homebuilding*, Constructability Press, Winter Park, Florida, 2011.
[12] Ratzer, A.V. and Wells, L. and Lassen, H.M. and Laursen, M. and Qvortrup, J.F. and Stissing, M.S. and Westergaard, M. and Christensen, S. and Jensen, K. CPN Tools for Editing, Simulating, and Analysing Coloured Petri Nets. In *International Conference on Application and Theory of Petri Nets*, pages 450–462, Berlin, Germany, 2003.