35th European Modeling & Simulation Symposium
20th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2023 The Authors.
doi: 10.46354/i3m.2023.emss.037

Increasing the output of prefab production lines - simulation aid to guide the improvement process

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Abstract

The walls of prefabricated houses are produced at dedicated production sites. The wall element production system in industrialized prefabrication is a special form of mixed model assembly line, where all the different walls needed to assemble a house on site are usually prefabricated on one or more lines. Each wall has different characteristics that affect the processing time of the activities at each work station. Special attention must be given to modeling design variants to cover the wide range of customer requirements and to ensure production feasibility. This paper presents a bottleneck analysis for this specific production process and shows how to link the product data with the processes in the discrete event simulation model built with SIMIO. The model has been validated with real production data. The simulation experiments consider several scenarios regarding the baseline scenario as well as material and sequence changes in the process and the flexibilization of the employee assignment. The results clearly reveal bottleneck workstations and provide guidelines for improving overall production output. A subsequent research project will test the use of the model for real-time production planning using online data from production.

Keywords: : Industrialized house building, production line, bottleneck analysis

1. Introduction

A prefabricated house is built on a prepared substructure consisting of storey high large panel wall elements, room cells and ceiling and roof elements. These are manufactured in the production sites regardless of outside weather conditions and are then transported and assembled on the construction site. Prefabricated houses are distinguished based on where the modular construction is taken place. A non-volumetric pre-assembly consists of elements, like wall panels, structural sections or pipework, assemblies, that are connected to other elements only on the construction site whereas volumetric pre-assembly already encloses a usable space before arriving at their final position, for example, toilet pods or modular lift shafts.

Figure 1 shows a schematic overview of the production process. Some of these processes can overlap in the real system. The production process of a prefabricated house normally starts with deciding on a strategy about how and when the product is sold depending on the varying degrees of customer involvement. Potentially, the design is specified with the customer. Once the design and the construction dates are specified, the production process is started.

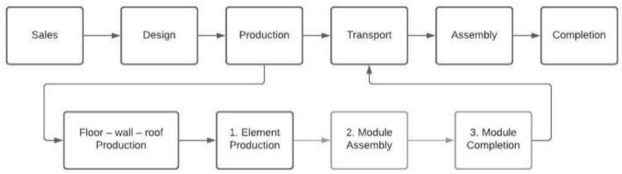


Figure 1. Schematic representation of prefabricated houses production process (modified from (Meiling 2010))

2. State of the art

The production process of a prefabricated house is comparable to the assembly line of a general manufacturing plant. Most stations are still manually operated and workload balancing between such stations is the most urgent problem. Gronalt and Hartl (2003) describe this issue for low volume truck manufacturing. Gartner et al (2023) develop an approach for job and product rotation for industrialized housebuilding production facilities.

Modern simulation tools are used to develop simulation models to evaluate assembly line configuration and balancing problems (ALBP). Das et al. (2010) use computer simulation to analyse an ALBP with variable task times. Xie, et al. (2011) used discrete event simulation (DES) to analyse underlying problems in the production line and a what-if analysis to improve the performance of production lines of prefabricated houses. Tiacci (2012) created an event simulator for different assembly line configurations and Tiacci (2015) combined DES with a genetic algorithm approach to solve the ALBP. A case study by Erikshammer et al. (2013) showed that DES could serve as decision support for the relevant construction company. Bathia et al. (2022) apply a simulation-based planning process for modular construction manufacturing lines using historical and near real-time data.

However, simulation models to evaluate prefab production lines are very rare. This paper contributes to narrow this gap: It shows how to use product data as variable input for the simulation model and it applies guided simulation experiments to identify bottlenecks in the production lines.

3. Simulation model Development

3.1. Conceptual Model

Error! Reference source not found. outlines the conceptual model of the outer wall production line. Each station is named after the task that takes up the main time in the station.

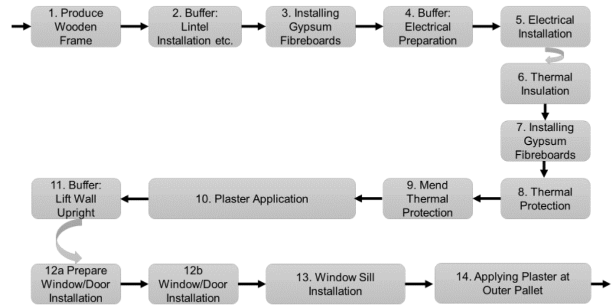


Figure 2. Conceptualization of the outside-wall production process

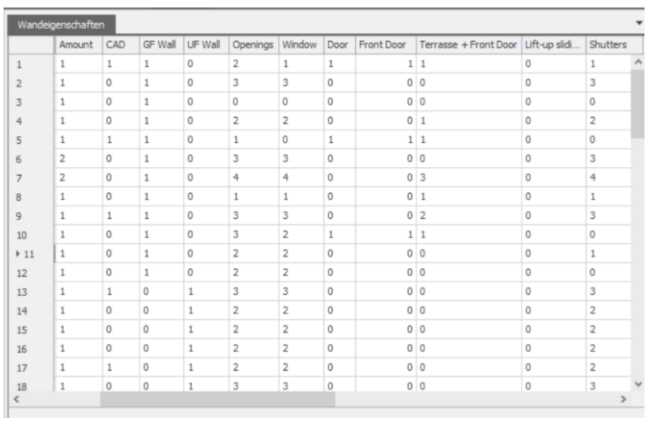
In Station 1 the wooden frame of the wall is constructed. Station 2 is a buffer station where some preparation works like installing the lintels are done. In Station 3 the main task is mounting the gypsum fibreboards. Station 4 is also a buffer station where some preparing tasks for the electrical installation are done. In Station 5 electrical assembly is installed. Between Stations 5 and 6 the wall is turned around. The main task in station 6 is to bed the thermal insulation into the wall. The central task in Station 7 is to cover the wooden frame with gypsum fibreboards. The key task in Station 8 is to cover the gypsum fibreboards with a thermal protection layer. In Station 9, holes in the thermal protection are mended. In Station 10 the wall is covered with plaster. Station 11 is another buffer station where the wall is lifted into an upright position. Station 12 was split into two stations in the model because it fits two walls. In station 12a preparation works for installing the window or door are performed. In station 12b the window or door itself is installed in the wall. In station 13 the window or door sills are mounted. Finally, in station 14 the window frames are covered with plaster.

Figure 3 is an adaptation of Steinhauer's and Soyka's (2008) approach to use a database to increase the flexibility of a model. There are two different kinds of properties in the spreadsheet, numeric and binary ones. Numeric properties give the number of objects on a wall such as the number of windows, doors, shutters etc. In the case of binary properties whether the wall has this specific attribute (with a 1) or not (with a 0). The property ("Amount") shows the number of walls that can be processed at one time. Because if the sum of two walls is 12 meters or less they can be processed together.

Table 1. Stations and assigned number of workers

Task Nr.	Description	Conditions	Distribution	Min [min]	Mode [min]	Max [min]	Nr. Of Workers
61	PU foam application	None	Triangular	12,67	18,49	24,17	1
62	Cut out corner fabric to Z-profile, clip on & staple in place	Only ground floor walls	Triangular	1,33	2,55	5	1
63	Apply paper tape to windows and door openings	Number of window/door openings per wall	Triangular	0,17	0,34	0,9	1
64	Attach paper foil to upper and lower flange	None	Triangular	0,93	1,48	2,7	1
65	Transport wall to station 10	None	Triangular	0,83	0,9	1,13	1

Station	Number of workers
Station 1	2
Stations 2 and 3	2
Stations 4 and 5 (for specific tasks of station 6/7)	1
Stations 6, 7, 8 and 9	9
Stations 9 and 10	3
Station 12	3
Station 13	3
Station 14	2


Wandeigenschaften

	Amount	CAD	GF Wall	UF Wall	Openings	Window	Door	Front Door	Terrasse + Front Door	Lift-up slidi...	Shutters
1	1	1	1	0	2	1	1	1	1	0	1
2	1	0	1	0	3	3	0	0	0	0	3
3	1	0	1	0	0	0	0	0	0	0	0
4	1	0	1	0	2	2	0	0	1	0	2
5	1	1	1	0	1	0	1	1	1	0	0
6	2	0	1	0	3	3	0	0	0	0	3
7	2	0	1	0	4	4	0	0	3	0	4
8	1	0	1	0	1	1	0	0	1	0	1
9	1	1	1	0	3	3	0	0	2	0	3
10	1	0	1	0	3	2	1	1	1	0	0
11	1	0	1	0	2	2	0	0	0	0	1
12	1	0	1	0	2	2	0	0	0	0	0
13	1	1	0	1	3	3	0	0	0	0	3
14	1	0	0	1	2	2	0	0	0	0	2
15	1	0	0	1	2	2	0	0	0	0	2
16	1	0	0	1	2	2	0	0	0	0	2
17	1	1	0	1	2	2	0	0	0	0	2
18	1	0	0	1	3	3	0	0	0	0	3

Figure 3. Wall property table

3.2. Simulation Model

The Base Model starts with a source that creates entities. These entities are walls and are processed in the workstations or servers. They are delayed in the model for a certain time in a workstation for the defined duration of the specified work steps. Material availability is assumed to be consistent and without variability. For each of the stations shown in Figure 2 the dedicated processing steps and the required workers are modelled in detail by using the process logic features of SIMIO.

The processing time is calculated by using the attributes from Figure 3. Wall property tableand a standard time for each activity, which is taken from the ERP System. The model without modifications is named Base Model. In the Base Model, it is assumed that each task always needs the same number of workers as given in Table 1. Some stations have their own worker pools, while others share their workers with other stations.

The single worker entity in Stations 4 and 5 is an electrician and also performs electrical tasks in other stations. Stations 6, 7, 8 and 9 share their workers.

The data of the 10 most produced types of houses were used as a reference and the number of specific elements of the walls was counted. The following objects were taken into account: openings for doors and windows and separately doors, windows, terrace doors, lift-up-slide doors, the number of shutters and then separately either with electric or manual opening systems, the number of ventilation systems, the number of outside-electric systems also separate to electricity plugs or switches, if factory plaster was used or not and if boxformwork was used or not.

In the following, we show the simple process logic of station 9 and the used data tables. Figure 4 shows the behaviour of Station 9. Station 9 consists of five tasks. The duration of each task has a triangular distribution.

Table 2 shows the description of the tasks and their processing time distribution. Task 62 happens only for ground floor walls with doors to the outside. Task 63 is dependent on the number of windows or door openings per wall. If a wall doesn't meet the specific requirements of that task its processing time is zero. For all tasks at least one worker is necessary.

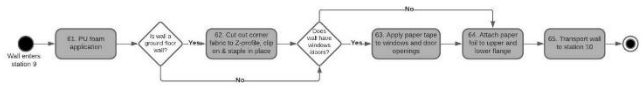


Figure 4. Process logic of station 9

4. Experiments

The **Base Model** reflects the current state of the work processes. The experiments are compared with this one to show the changes.

There are three different kinds of changes that were examined: flexibilization of workers, structural changes to the process, and changes in material. Two variants were used to test the impact of worker flexibilization. In Variant 1 pools of workers with different qualifications, such as electricians or carpenters are assigned to all the tasks depending on what qualification is needed. In Variant 2 in certain activities, additional workers are taken if enough are available which reduce time in these tasks. Changes in material can reduce processing times for example because they help reduce processing steps. These Experiments have to be coordinated with the suppliers. The New Adhesive Experiment is a material change. Structural change can be either a change of processes in which activities are carried out in parallel or additionally. The thermal insulation, activity shift and lift-slide door Experiment include structural changes.

For any of the experiments either the process logic or the input data or both is modified in the simulation model. We will now present the experiments shortly:

Flexibilization: the worker pools are sorted by qualifications and the strict assignment to one specific station is lifted.

Flexibilization with Time Reduction: there is an additional decrease of processing times for certain tasks if an additional worker is assigned to some specific tasks.

New Adhesive: it is assumed that a new adhesive is used that dries so quickly that the work steps of clamping and foaming are omitted.

Thermal Insulation: the cutting of the thermal insulation takes place externally.

Activity Shift: various activities are shifted to the subsequent station.

Combination: all the changes of the previous Experiments are combined. All in all, 85 variations of this Experiment were conducted to find the variation that produces the most walls in the same amount of time.

Lift - Slide Door 1: the installation of lift-slide doors is also considered.

Lift - Slide Door 2: the installation of lift-slide doors

For each replication, the average time or utilization per wall of one simulation period is calculated. The simulation period of one experiment run is 4 days. Each variation was run 20 times.

5. Results and Discussion

The results displayed in Figure 5 clearly show the most promising actions to improve the production line output. Flexibilization with time reduction is the most promising one. But it requires additional analysis to figure out the time reductions possible. Also, a mix of measures can reduce the average time of production. On the other hand, some equipment options may bring some pressure to the overall line performance.

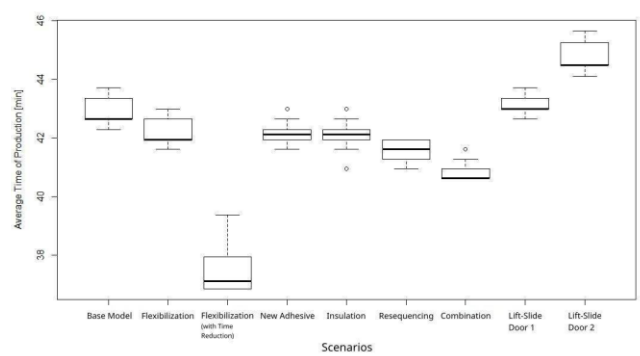


Figure 5. Average time of production per wall for the different experiments

According to Larsson and Rudberg (2020), waiting times need to be analysed very carefully since their direct cause often cannot be determined. In this model, only waiting time caused by either the shortage of

Task Nr.	Description	Conditions	Distribution	Min [min]	Mode [min]	Max [min]	Nr. Of Workers
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65	Transport wall to station 10	None	Triangular	0,83	0,9	1,13	1

Table 2. Tasks description and processing times

workers or the non availability of the subsequent station have been considered. Other reasons for waiting times are disregarded. Furthermore, in the model only value-adding activities were taken into account when defining the different experiments. Waiting times are often used to perform non-value adding but still necessary side-line activities such as refilling material in a machine.

In the Combination Experiment, all the parameter and process changes of the previous experiments are combined. All in all, 85 variations were conducted to find the variation that produces the most walls in the same amount of time. Figure 6 shows the reduction in the work stations' utilization. With this setting the utilization at the bottleneck stations AW6, AW7 and AW8 is reduced.

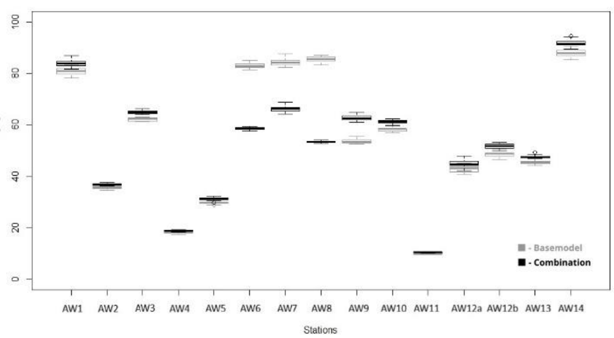

Figure 6. Utilization of the stations. The base model in gray, the combination experiment in black.

6. Conclusion and Further Research

A Simulation model has been developed to analyze the behavior of a production line for outer walls of a company producing prefabricated housing while running through 8 different experiments with over 180 variations. The biggest advantage of the model is the ability to test alternative set-ups at the sole cost of the development of this model and therefore avoiding unnecessary investment costs. It also provides a guideline for the production managers to develop a measurement system to increase the production output. The use of a spreadsheet to access the different wall properties and time parameters for each task facilitates the implementation of changes. This also makes the model adaptable and the usage of statistical distributions for particular processing steps shows the variability of the system's output and enables the examination of its effects on the system.

Next steps will be to expand the model for the inner wall production line and to setup an integrated simulation model for the whole production site. This will require an overall data management approach, which automatically generates and provides task dependent processing time for the simulation.

Further work will supply the simulation model with real time production data collected via RFID for on-line production control.

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