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# SEQUENCING THE PRODUCTION OF MASS CUSTOMIZED WALLS

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**Abstract:** *House building has moved indoors, into factories that mass produce flooring, walls, and roofs in dry and controlled environments. Since projects differ, and sections of the same house differ, the production system follows a mass customization philosophy, trying to make one-of-a-kind products efficiently. However, producing different products with different processing requirements and times in the same production line presents challenges, such as waiting time at the different stations in the line. The challenge is to obtain a balance between the different stations, considering variations between the products such as size, type of facade, number of windows and doors, etc. This study focuses on the production line for exterior walls at a company manufacturing house elements. Our findings show how the use of simulation with an optimization function improved the throughput by 8.8% by adjusting the sequence of the products.*

**Key Words:** ***Simulation, Sequencing of jobs, Optimization of throughput***

## 1. INTRODUCTION

Industrialized prefabricated house building represents a significant advancement in the construction industry. The method entails producing parts or entire sections of a house in a factory setting before it is transported and assembled on-site. Prefabrication has evolved significantly in later years and now utilizes a range of modern technologies and processes to enhance efficiency and quality.

Some notable advantages of prefabricated house building are increased efficiency and reduced build time, improved quality control, and waste reduction (Li et al., 2014).

Today, most new houses are made according to customers' preferences and are unique in size and shape, drawn by an architect, and planned by an entrepreneur before ending up as individual contracts. This also goes for other buildings, like schools, kindergartens, shopping malls, etc. Buildings tend to be unique to an ever-increasing percentage. Earlier, buildings were made up of more standard solutions than today, and factories could be planned based on repetition and experience from variants.

The case company in this research has a plant for manufacturing house elements. Following the increased demand for customization from their customers, they have seen a fall in efficiency on their industrialized line for manufacturing exterior walls, as well as increased queuing and waiting situations. The walls are made in a production line that consists of 8 stations for structure, insulation, plate covering, windows, lathing, exterior panelling, framing, and packing.

Producing a large variety of customized products with greatly different processing times in the same line can create excessive waiting times reducing the overall performance of the production line. There is a need to find solutions that enable the manufacturer to offer customized products with industrialized efficiency. Producing the walls in a production line offers specialized stations, increases standardization, and creates a flow of products throughout the production facility. At the same time, in case of variance between products and imbalances in production time, a line can also experience significant waiting times reducing the practical capacity of the line. This paper investigates the potential of finding the optimal production sequence considering operational capabilities in the existing line by studying real data from one month of production of a variety of walls.

The paper is organized as follows: Section 2 introduces the empirical and theoretical background for this study, while Section 3 describes the research method used. Section 4 presents the results, while Section 5 discusses the findings and their implications. Section 6 concludes the paper and presents directions for future research.

## 2. EMPIRICAL AND THEORETICAL BACKGROUND

### 2.1. Case overview

The case company in this study produces prefabricated house elements in a factory with several different production areas, including areas for roofing, exterior walls, interior walls and flooring.

When a contract for a new building is granted, the engineers split the buildings into manageable parts for industrialized pre-fabrication, and manufacture modules in-house before transporting them to the construction site. Different areas of the factory produce different parts of the building before they are shipped to and assembled on the construction site.

The focus of this study is the exterior wall production area, where the walls are built in a production line with 8 stations. The stations are for structure, insulation, plate covering, windows, lathing, exterior panelling, framing, and packing. These stations are connected by a conveyor that transports the walls to the next operation, and the line has limited buffering capacity. This means that the stations are dependent on a balanced takt time to obtain a smooth production flow.

Although the factory produces highly customized exterior walls, all the walls go through the same production line. The products vary greatly in required processing times, and as there is limited buffering capacity and no "overtaking" possibilities in the line, there is a lot of waiting time for the stations. In this line, there are two main causes of waiting time. The first is the situation where the station is waiting for products from the preceding station ("idle time"). The other is situations where the station is finished with its operations on the product but cannot send it further down the line because the following station is still occupied ("blocked time"). Such waiting times reduce the productivity of the line and increase the makespan of the planned production.

To reduce the makespan and thus make it possible to increase the production output of the line, several strategies can be applied.

The first strategy is to do a (re)balancing of the line, by (re)assigning the different tasks to the different stations to obtain a more equal process time (takt time) across the stations along the line. In this case with the production of customized walls, this can be challenging as the process requirements between the different walls vary greatly. Some walls are quick to produce, with dimensions close to standard, no complex geometry, and without windows or doors. Other walls can have complex geometries, unusual dimensions, a door, and several windows.

Another weakness with the line is that there are no possibilities for the simpler products, for instance, walls without windows, to skip the window station and "overtake" the slower products. Getting the faster products down the line to available stations waiting for work is expected to increase the utilization of the line. Furthermore, except for two smaller buffers, there is little buffering capacity along the line to balance out the imbalances in processing time. Such "physical" adjustments to the line as adding overtaking possibilities or additional buffers are expected to increase the utilization of the stations.

A third approach to increasing the production throughput is adjusting the sequence of the products. An unfavourable sequence of products can create extra waiting time for some stations. For instance, releasing a "quick" product right after a "slow" product can lead to stations being blocked from sending products down the line, while the opposite scenario can create situations where stations are waiting for products. This study focuses on investigating the impact of production sequence in a production line with mass customized products.

### 2.2. Earlier research

Existing research has targeted several different areas related to industrialized prefabrication of walls for house building, including the adoption of mass customization. Schoenwitz et al. (2017) address the importance of aligning product, process and customer preferences to improve customer satisfaction and operational performance. Larsen et al. (2019) investigated, through a literature review, the state of the art in mass customization in the house building industry. Their findings indicate a potential for mass customization in the house building industry, although the research is scarce and the field rather unexplored. Eid Mohamed & Carbone (2022) provides a framework for mass customization in house building, aiming to balance individual customer needs with the benefits of industrial prefabrication, focusing on the stages before production.

While prefabrication is a common method for adopting mass customization in the construction sector, guidelines for adoption have also been suggested in the context of house-building companies that adopt traditional construction technologies (Formoso et al., 2022).

There also exists some research targeting sequence optimization in industrialized house building. Liu et al. (2023) focus on optimizing the assembly sequence of prefabricated building components and introduce a simulated annealing genetic algorithm for this purpose. Their findings show that it outperforms traditional methods, reducing assembly time and minimizing interference during the construction process. Nam et al. (2020) also focus on the assembly process to improve overall project delivery times, using simulation of a virtual case to show the potential for optimizing the process. Finally, Altaf et al. (2014) showed, through a case study of a wood-frame panel fabrication plant, that simulation and particle swarm optimization can improve the sequencing of production, with results indicating a potential of up to 10% increased productivity.

As shown, there has been some research on mass customization within this type of production, but there are still unexplored areas. For instance, there has been less focus on how to rig your production lines/processes (including sequencing) to effectively handle mass customized house production.

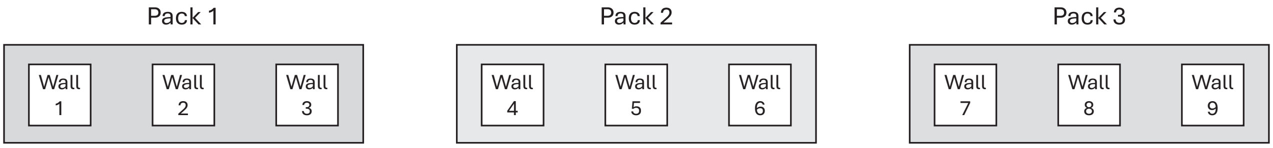

Fig. 1. *The established manufacturing logic adopts to the preferred assembly sequence, packing in packs of 3 walls*

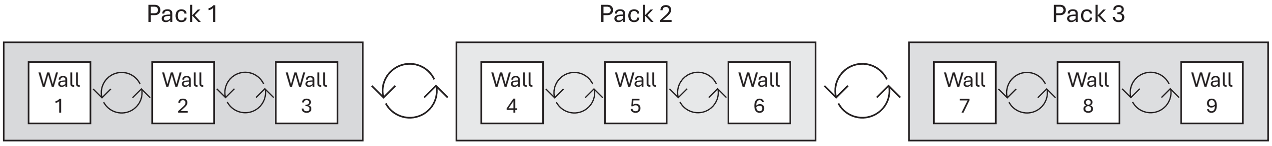

Fig. 2. *The sequence was shuffled whilst maintaining the company's policy of packing walls according to assembly sequence*

## 3. RESEARCH METHOD

Through visits to the case company, discussions in workshops, and company documentation, a discrete-event simulation model of the production line was created in the software FlexSim.

As input to the simulation model, the case company provided data on one month of production. The month was considered a typical month for the company, where 110 walls for 7 different projects were produced. For each of the walls produced that month, the data included product characteristics, such as the wall's project ID, the length of the wall, and the process times for each process along the production line. This data was first used to validate the simulation model, and the results showed a simulated performance of the line similar to the actual performance for that month.

To try different production sequences, the optimizer addon OptQuest was used. The optimization objective was the production makespan, i.e., the time from the first product in the batch was started until the last product was finished.

However, to maintain the company's policy of packing the walls in groups of 3 according to the assembly (or installation) sequence on the construction site (Fig. 1), two constraints were added to the optimization:

- The walls still need to be packed in groups of 3 according to the assembly sequence, but the sequence in each pack can be shuffled (e.g., 1-2-3, 1-3-2, 3-2-1, etc.)
- All the walls for the same projects are produced together, but the sequence of the packs of 3 walls can be shuffled.

This is illustrated in Fig. 2. Even for a single project with 24 walls (8 packs of 3 walls), there are around 67.7 billion potential sequences[1]. That is far too many combinations to test individually in the simulation. To navigate the solution space and quickly find improvements, OptQuest uses a combination of heuristic search techniques (Kleijnen & Wan, 2007). With this many possible combinations, the optimization algorithm most likely did not find the theoretical optimum in the number of trials we ran. However, we did see major improvements already after a few hundred trials, indicating the efficiency of the optimization algorithm.

## 4. RESULTS

The baseline simulation showed that using today's production sequence purely based on the assembly sequence, the total makespan for the 110 walls produced that month was 159.35 hours. The extent of waiting time along the line is also evident in the cumulative numbers of idle time (time waiting for a product) and blocked time (not being able to send the product downstream). In the baseline scenario, these types of waiting times across all production line stations summed to 259.04 and 359.68 hours, respectively. The average utilization across all the production line stations, calculated as the ratio between the time stations spend working on products and the available production time, measured 55%. The extent of the waiting time and the average utilization, suggest that the production line still has a significant potential to increase its output.

After the model was constructed and validated using the baseline scenario, we used the OptQuest addon for FlexSim to simulate alternative production sequences. Based on our observations of long waiting times, both due to waiting for products and because of a blocked production line, we expected that a more controlled sequence of products would reduce the waiting times and increase the throughput of the production line.

The optimizer addon was then used to run numerous simulation trials to find the optimal solution based on our performance objective of minimizing the production makespan. The exact number of simulation trials to run to get satisfactory results is hard to determine in advance. Literature typically points towards a minimum number of trials based on the number of decision variables (Forbus & Berleant, 2023). However, it does not point out the optimum number of trials as this is highly case-specific. In this study, it was decided to use a graphical method to determine the sufficient number of trials. Based on the real-time display of simulation results, the optimization was stopped after 1000 trials without further improvements to the performance objective. This resulted in 4248 simulation trials.

Table 1 presents one of the simulated sequences (Trial 3248) that had the largest improvement in production makespan (several sequences obtained this result). As shown, there is a notable improvement in the production makespan, saving 14 hours over the simulated period. This equals an improvement of 8.8%, which equals close to 2 working days saved during a month. This is a result of reduced waiting time (idle and blocked time) and increased utilization.

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[1] $(3!)^8 \times 8! = 67\ 722\ 117\ 120$ combinations

Table 1. *Comparison of key performance indicators*

| **KPI** | **Description** | **Baseline** | **Trial 3248** | **Change** |
|---|---|---|---|---|
| Makespan | Time from the first product enters the production line until the last product leaves the line | 159.35 hrs | 145.35 hrs | -14 hrs (-8.8%) |
| Sum idle | The sum of the time periods where a station waits for a product from the previous station | 259.04 hrs | 229.80 hrs | -29.24 hrs (-11.3%) |
| Sum blocked | The sum of the time periods where a station cannot send a product down the line because the following station is not finished | 359.68 hrs | 298.12 hrs | -61.56 hrs (-17.1%) |
| Avg. utilization | Average utilization (production time/available time) across all stations | 55% | 60% | 5% |
| Max utilization | The utilization of the station with the highest utilization | 76% | 83% | 6% |

## 5. DISCUSSION

The results from the optimization indicated an 8.8% improvement potential in the makespan for the planned production of the investigated month. This improvement still adheres to the rule of packing sequential walls in the same pack, however, not necessarily in increasing order. This approach to reducing the makespan is less resource-intensive, given that the adjustments are purely related to planning and control, and no physical investments are needed.

To see the full potential of sequencing facilitating line efficiency, a model with no constraints was programmed. When running this model, all 110 walls can be considered the next wall to manufacture. This test gave a result of 128.35 hours, reducing the makespan additionally by a bit more than 2 working days.

Also, to further understand the performance of today's planning routines, a simulation was run to find the potential longest makespan, just to see how slow the worst sequence would be in this manufacturing setup using the same input data. The result from "optimizing" to find the longest makespan resulted in a total makespan of 180 hours, 2.75 working days longer compared to the plan in use. The explanation is most likely that when the sequence of walls is not planned with respect to manufacturing, but rather the preferred assembly order, and the number of walls in the batch is high, this sequence places itself approximately in the middle of the possible makespan interval, meaning that some parts of the total sequence are randomly good whilst others are randomly weak.

It should be noted that this study has been done using historical data to illustrate the potential. A challenge for the case company will be to classify the walls before manufacturing with respect to expected processing times in the different stations. Predicting exact processing times prior to production will be challenging as these are customized products. Instead, as a starting point, it should be investigated whether the products, after design and before production, can be classified into a few groups. The different groups should reflect the expected production complexity of the wall, which can be used as a predictor for processing time. Using a more simplified classification like this, rather than exact approximations of processing times, will likely mean that the full potential savings cannot be obtained, although we still expect that the improvement can be considerable.

The walls are suggested to be classified into one of 5 groups, depending on their dominating feature, to be available for optimization algorithms before manufacturing. Features necessary to consider include length, number of windows and doors, shape, finish, etc. Combinations of these features influence how complicated and hence time consuming the walls will be in each station. Wall classes derived in the project were (simplified):

- **Class 1:** Closed walls (no doors or windows), or no wooden panelling
- **Class 2:** Walls with 1-2 windows/doors, horizontal panelling
- **Class 3:** 3 windows or more, vertical wooden panelling
- **Class 4:** Rotated walls (height > 3.2 m), multiple plate layers
- **Class 5:** Walls that should not enter the line, due to being too long, too low, change in height over the length, etc. Must be hand-crafted.

To improve the classification of designed walls, the company should continue to gather and analyse historical production data, to build better predictive models of expected processing times for new walls. Although the walls are customized to unique projects, there are still many similarities to earlier produced walls which can be used to improve the processing times estimations. The evaluation of new designs using historical production data will improve as increasingly more data becomes available. The predictive capability can also be improved by taking advantage of recent improvements in predictive modelling fuelled by advances in artificial intelligence (AI).

## 6. CONCLUSION

Producing a large variety of products in high volumes imposes substantial requirements on the production system. There are numerous strategies and approaches for how to ensure industrial efficiency of such operations. This paper focuses on the production of customized prefabricated house elements and investigates the impact of production sequencing on the overall performance of the production line. The following learnings are noted:

- The sequence in which products are made can have a significant impact on total productivity
- Finding the ideal sequence demands efforts and analysis up-front

- Simulation proved to be helpful in showing the potential of optimizing the sequence of products in a project
- The case company accepts a sequence suited for efficient assembly at the building site, not the manufacturing of walls in-house. Producing according to the assembly sequence turned out to be approximately in the middle of the interval between the shortest and longest possible production makespan.
- The model used for the analysis of sequences can be expanded to take on tasks of experimenting with alternative line designs

A limitation of this study is that the study only investigated one month of production data. It could be valuable to extend the period to understand how the solution performs over longer periods with different product mixes.

Relevant future work includes experimenting with different line designs, such as double tracks for ease of individual flow, or adding stations between operations to even out short queues and imbalances. A challenge is to classify walls before putting them into production to foresee the impact they have on the different stations down the line and make a holistic optimal plan. It should be investigated how the optimization model can be integrated into the company's production planning systems. Moreover, the use of AI in optimization is continuously developing offering new possibilities going forward.

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