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ON-SITE ASSEMBLY OF MODULAR BUILDING USING DISCRETE EVENT SIMULATION

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ABSTRACT

With the continuous development of industrialization in building construction, modular construction and off-site prefabrication methods have been applied much more thoroughly and comprehensively to achieve higher efficiency and better quality control as the major building components are able to be produced in a factory setting, which reduces the influence of uncontrolled factors. This paper, while employing discrete event simulation, uses Simpony.NET tool to model the process of transporting modules and assembling them on the construction site of a future multi-residential project. By adding more details, such as the weather and traffic conditions, the simulation results can become more accurate. In addition, as most simulation models for modular construction processes focus mainly on the assembly of modules on site, this paper also quantified the weather influence in terms of project duration and manpower utilization. Furthermore, the simulation model could also provide a general guide for the comparison of various scenarios.

1 INTRODUCTION

Housing is very important for the survival of humankind and it plays a key role in the economic development. In the present time, affordable housing has become a serious issue (Panjehpour and Abang 2013). To overcome this serious issue in 20th century, pre-fabricated buildings have gained popularity and the Modular Building Institute (MBI) was established in 1983. (Han et al. 2012). According to MBI, modular construction can be defined as “a process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards”. In this method, buildings are constructed from different sizes of modules, which are made in a facility and then transported to the site where they are assembled together, which reflects the identical design and specification. Modular construction methods are becoming more and more familiar worldwide due to their more environmentally friendly construction process; the use of this technique can also reduce construction time and material waste, improve air quality, and also eliminate weather delays (Han et al. 2012).

It is well known that construction operations are repetitive and are subjected to many resource constraints, which can lead to uncertainties or interruptions in the process. There are many other factors such as weather and site condition, which can also lead to an interruption in construction. The best possible remedy for these interruptions is the use of computer simulation, which can show the impact of different conditions and make it possible to plan a course of action (Song et al. 2008).

Computer simulation is the responses of one system due to the behavior of another system modeled after it (Encyclopedia Britannica 2019). The simulation uses mathematical descriptions, graphical constructs, computer algorithms and other means that are summarized in the simulation software model to represent the real system. It can be used to eradicate bottlenecks, to use resources more effectively, and to optimize the system performance before an existing system is altered by a proposed design. The construction industry is using many developed simulation tools (AbouRizk et al. 2016).

This project is about on-site assembly of four, three-story buildings in Michener Park Edmonton, Alberta, Canada. The different sizes of modules, ranging from 39,000 lb to 72,000 lb in weight, are to be built off-site in the facility and transported to site using trucks. In addition, constraints are to be applied, such as only one crane can be used to lift the modules due to the geometric limitation of the site, only limited space is available to store the modules on the site, and the process of construction can be affected by the transportation of the modules and weather conditions. The project has a fitting and welding crew that are responsible for erecting or assembling the modules on the site.

This paper developed a simulation model using Simphony.NET general purpose template. Simphony is a user friendly and highly flexible simulation tool that can accurately model complicated system in construction domain. It also enable user to control different simulation behavior in the simulation model (AbouRizk et al. 2016). The simulation model developed satisfied all the constraints discussed above and by changing the condition of the process such as the crew selection and manpower combination, different scenarios are able to be compared without actual execution. In addition, the final results of the model in regarding to the project duration can also be a fairly accurate reference for the future work as most of the factors which could potentially impact the project were considered in this model.

2 LITERATURE REVIEW

In the construction industry, decision making is always of critical importance. The use of simulation models can assist in the decision making. (Hassan and Gruber 2008) successfully implemented a simulation model in a civil engineering operation and determined that these models help decision makers and strategists to assess different resource combinations to achieve higher accuracy compared to relying only on experience. (Kim and Kim 2010) used multi agent based simulation to evaluate the traffic flow of construction equipment in the construction site and to study the effect on the efficiency and productivity of construction site. The author find out that efficiency of equipment and estimated duration can be assessed using simulation and it can help in decision making for selecting alternate approach to complete the project within timeline. (Gonzales and Echaveguren 2012) studied the effect of simulation on sustainability on the road construction process to reduce the emission of gases using discrete event simulation and he successfully found the optimum number of trucks and loaders to make the environment sustainable and the complete the project within time. (Zayed and Halpin 2001) used simulation sensitivity analysis for decision making and resource management and came up with an alternative solution that minimized production time and cost, they also used simulation successfully for resource management and best route selection for transportation. (Han et al. 2012) demonstrated that simulation assists the project manager to understand the effect of changes to the process. The project manager can simulate these changes to improve the process before implementation in the real world situation, which will save time, decrease rework, and reduce cost. (Alvanchi et al. 2012) applied discrete event simulation for off-site construction planning to improve the fabrication plan and meet all the constraints in the project. It was very challenging to achieve all the constraint regarding fabrication plan and make an improvement to the plan, but the use of DES made it possible. The project was done with minimum conflict between fabrication and erection phases by fulfilling all the constraints of the project and the fabrication duration was reduced by 10% through adjusting the fabrication operation. (Alzraiee et al 2015) used simulation for estimating project duration, cost and productivity and comparing results with traditional planning methods such as CPM and PERT. It is noticed that there is significant difference for the outcomes as the project duration has significantly increased from planned duration. Because the dynamic behavior of the project execution is considered in the simulation and the results are more realistic and accurate.

3 DATA COLLECTION AND ASSUMPTIONS

The modular construction and assembly is based on the project from the Muhlenberg College (Olearczyk et al. 2007a; Olearczyk et al. 2007b). The two reports outline the general procedure followed for that modular construction project and the same sequence will be simulated in this theoretical situation.

For this project, module production in the factory is not considered in the simulation and it is assumed that modules are ready for pick up in the factory. The factory is located about 120 km from the construction site and it will take about 2 hours for the truck to reach the site without any delays. The delays considered in this model are categorized as major and minor delays with different time distribution collected from historical data and experienced experts, as shown in in Table 1.

Table 1: Time Distribution for Trucks Delays.

Tasks	**Distribution**	**Distribution Parameters**
Major Delays	Beta	0.8,1.7,25,38
Minor Delays	Beta	1,0.85,5,15

There are two different sizes of modules, categorized as small and large modules, and each module goes through the process of hooking/unwrapping, unhooking, welding, crane operating, backing the module in for crane pick-up and covering modules if unwrapped before they can be placed. Each module has its own time distribution collected from historical data, expert opinion, and experience based on similar types of projects. The time distribution and parameter numbers for each type of task are shown below in Table 2 and Table 3 for large modules and small modules, respectively.

Table 2: Time Distribution for Large Modules.

Tasks	**Large Modules**	
	Distribution	**Parameters**
Unwrapping	Triangular	15,25,20
Folding Trap	Triangular	10,25,15
Spreadbar Installation	Triangular	15,30,20
Hooking	Triangular	15,20,17
Crane Operation	Triangular	5,10,7
Securing-Lining Up	Triangular	15,30,20
Securing-Bolting together	Triangular	15,30,22
Unhooking	Triangular	7,10,9
Welding	Triangular	30,60,40

Table 3: Time Distribution for Small Modules.

Tasks	**Small Modules**	
	Distribution	**Parameters**
Unwrapping	Triangular	10,20,15
Folding Trap	Triangular	5,15,10
Spreadbar Removal	Triangular	15,30,20
Hooking	Triangular	8,20,17
Crane Operation	Triangular	5,10,7
Securing-Lining Up	Triangular	12,25,18
Securing-Bolting together	Triangular	8,20,15
Unhooking	Triangular	6,9,7
Welding	Triangular	28,60,40

Added detail to the model is the Markov Chain that will allow us to include weather into the simulation. Weather is based on historical data from a ten-year range (Weather Data 2019). The assumption is made that our project will take place in June, which means that extremely cold weather is not considered and our project will not be halted for that reason. When determining how the weather can affect operations, (Deckcrane 2015) states that wind, temperature, and rain can all affect when the crane can be in operation. Temperature affects a crane mainly in very low temperatures (de-rating factors should be implemented when temperatures reach -15 °C), but from the data gathered there should be almost no situation where the temperature would reach a level that would require a de-rating factor to be implemented. Removing the temperature data, the rain and wind data for every day is checked for a ten-year period in June for the Edmonton area. Wind speeds in excess of 20 miles per hour should stop a crane lift and postpone the activity until the wind stops (Deckcrane 2019). When rain occurs, visibility can lead to production loss and or effect crane performance, but every crane reacts differently in the rain and thus if it is raining, the module should not be unwrapped.

4 SIMULATION PROCESS

4.1 Modular Construction Process

Modular construction transfers most procedures of the construction process from outside to inside the factory and the only outside activity it requires is the module installation on site. Therefore, this simulation model mimics the process from the transportation of the module (factory to the field) to the on-site installation of the modules using a crane, which is essentially the whole process of the execution of modular construction except for the production of modules in the factory.

4.2 Project Description

Michener Park is a University of Alberta student residence for students who have dependents living with them. As the houses there are getting older, the relevant personnel in charge plan to demolish it in the next few years and construct a new residence district. This research has for its aim to simulate the construction process in advance to provide some reference and guidance, which is also the main application of simulation. The proposed building area is about 262 ft × 164 ft and will accommodate 4 similar 3-story houses as shown in Figure 1.

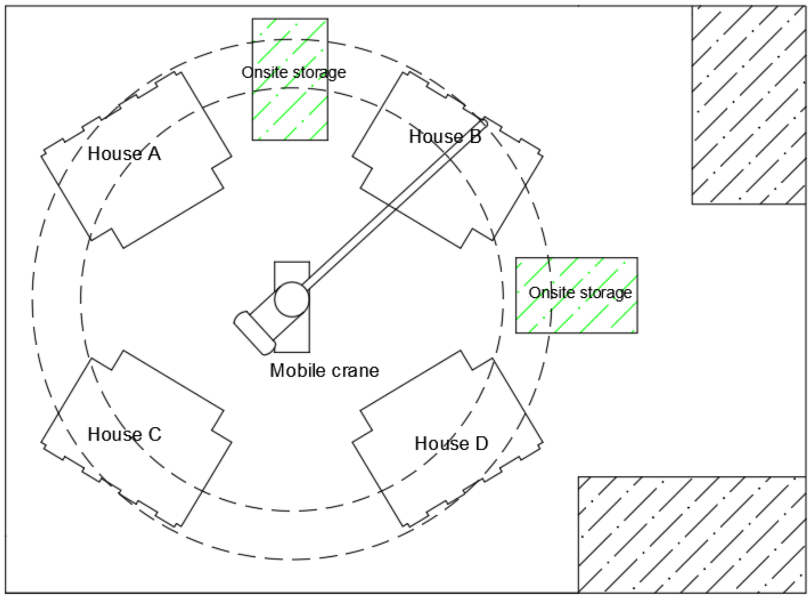

Figure 1: Site Layout.

The objective of this research is to simulate the construction process of this 4-house complex and each house is comprised of 18 modules (6 per floor). There are two types of modules ranging from 39000 lb to 72000 lb in weight and 22 ft to 51 ft in length, and each floor has 4 large modules and 2 small modules.

4.3 Model Description

4.3.1 Traffic Delay Part

The schedule of this project is based on installing one floor per working day, which means 6 modules (4 large modules and 2 small modules) per working day. The modules will be transported from the factory to site in the early morning, between 6 am and 8 am, just before the installation. Trucks are used to transport the modules and each truck is able to load 2 modules for one single trip. The "batch" element in Simphony.NET can simulate the truck loading as 2 modules batched together when departing and unbatched when they arrive. The distance is approximately 120 km and the travel time is about 2 hours without any delays. However, delays are somewhat inevitable depending on the traffic conditions on each day. Based on the data collected, there is a 30% chance of delay and 85% of the delays are minor delays, while a major delay might also happen 15% of the time. The duration of each delay type is assumed with a beta distribution. "Conditional branch" is used to model the delay scenarios.

4.3.2 Installation (Crane Lifting) Part

As can be seen in Figure 3, the modules that have arrived on site have to be unwrapped before installation. After that, folding and hooking can be started at the same time. When the hooking of the module is finished, the crane can do a set of operations including booming, swinging, etc. to move the module to its final set position. Then, the fitting crew will do the securing and lining up of the module to make sure the module stays in the right position. After all of those steps are finished, the welding crew can begin bolting and welding, while the fitting crew stays there to start the unhooking in parallel. After the unhooking process, the crane is released and able to move to the next planned position for the lifting of the next module. Finally, when the welding crew finishes its task, which means the module is finished.

Spreadbar installation or removal is another procedure to be added, because, for the large modules, the rigging system of the crane needs to be equipped with the spreadbar to ensure the modules are balanced during the lifting process. This step is only needed when the previous module's size is different from the current one, which would require the installation or removal of the spreadbar. In this case, for instance, when the previous module is large but the current one to be lifted is small, the spreadbar needs to be removed for the rigging system of the crane.

4.3.3 Weather Influence Part (Markov Part)

Weather is a huge factor in construction, which should be considered when running the simulation to obtain more authentic results. For modular construction, which requires the heavy use of cranes, the construction process could be severely impacted due to bad weather, such as rain or wind. Based on the weather data collected for Edmonton, as mentioned before, the weather's influence could be quantified by using the Markov chain in Simphony.NET. The basic logic is that the Markov chain will change state every 24 hours, or 1440 minutes, and that if the state is "sunny", activities and distributions will proceed as normal, when the state is "windy", the activity "unwrapping" of modules will be hindered by 10%, and if "rainy" the activity will be delayed until the state changes to "sunny" or "windy". The "crane lift" activity will be delayed if the state of the system is either "windy" or "rainy". The Markov model is shown in Figure 2.

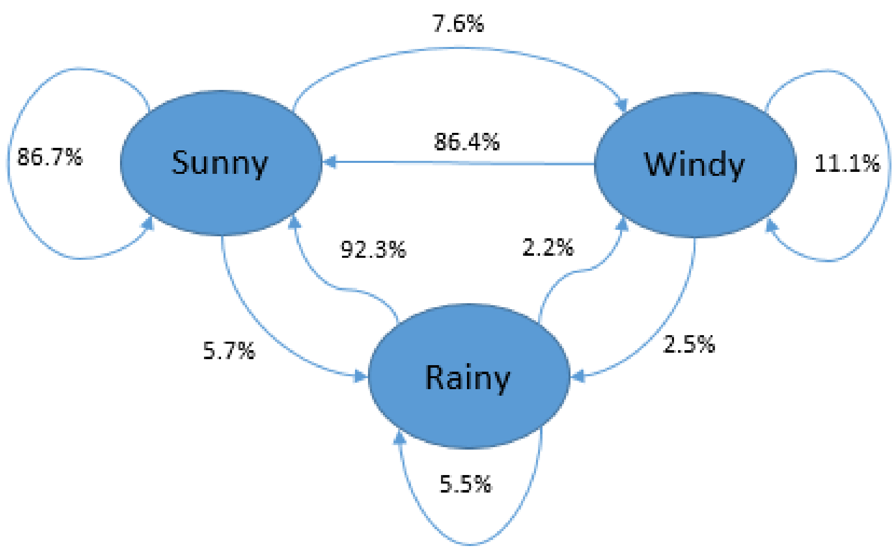

Figure 2: Weather Markov Model.

4.3.4 Model Layout

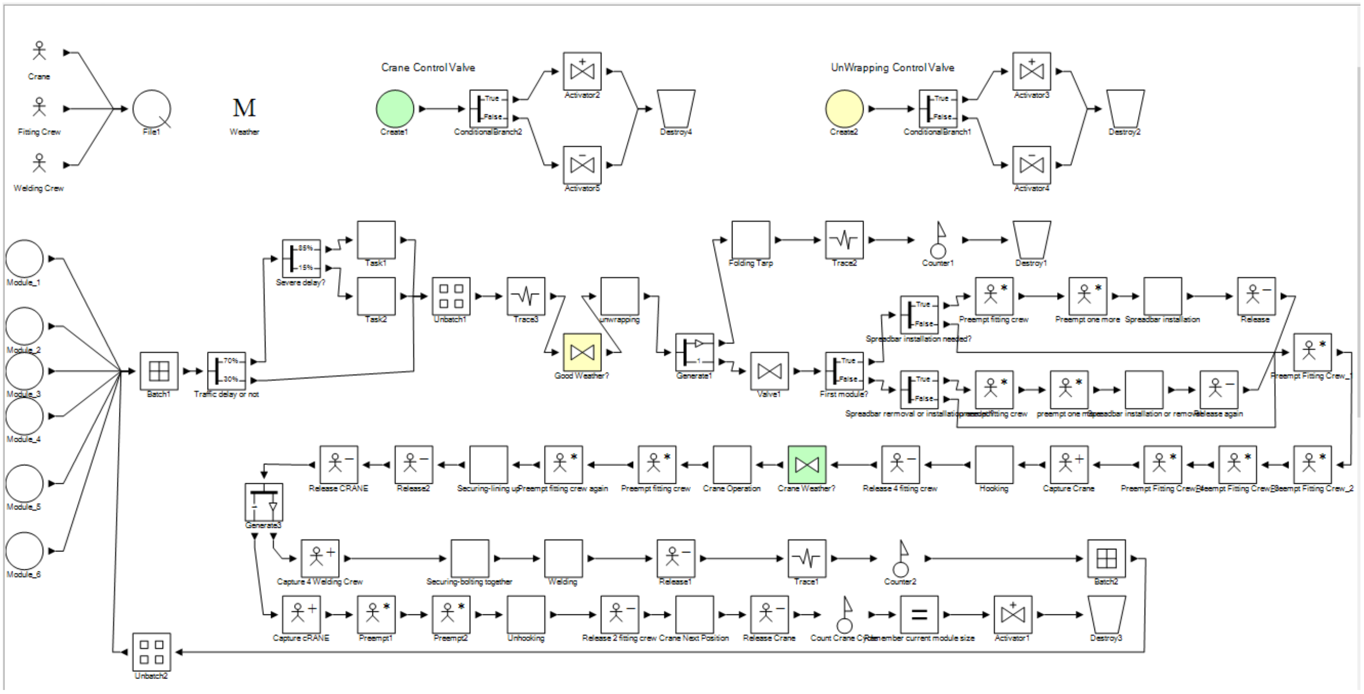

Figure 3: Simulation Model Layout.

Figure 3 above is the Simphony.NET model which just simulates the whole fore-saying process. At the beginning of the model, the modules have been produced and laid in the factory store waiting to be picked up, after that trucks just came and transported the modules to the site during which the transportation delay were applied and some of the modules in the same batch might experience different types of delays. Then, the module which arrived on site were unwrapped by the fitting crew and began its journey with the crane. After being lifted to the final position, the module needs to be welded by the welder crew as well to finish the whole cycle.

5 RESULTS AND DISCUSSION

After 500 runs of the simulation model, through considering different scenarios and satisfying all constraints, the results obtained are shown below.

5.1 Duration

The total duration of the project is 8003 minutes (133 hours) with a minimum duration of 6564 (109 hours) minutes and a maximum of 13326 minutes (222 hours); the standard deviation is about 1220 minutes (20 hours). The duration to complete one three-story building is around 1600 minutes (27hours). The cumulative distribution function (CDF) of the total duration of the project is shown in Figure 4.

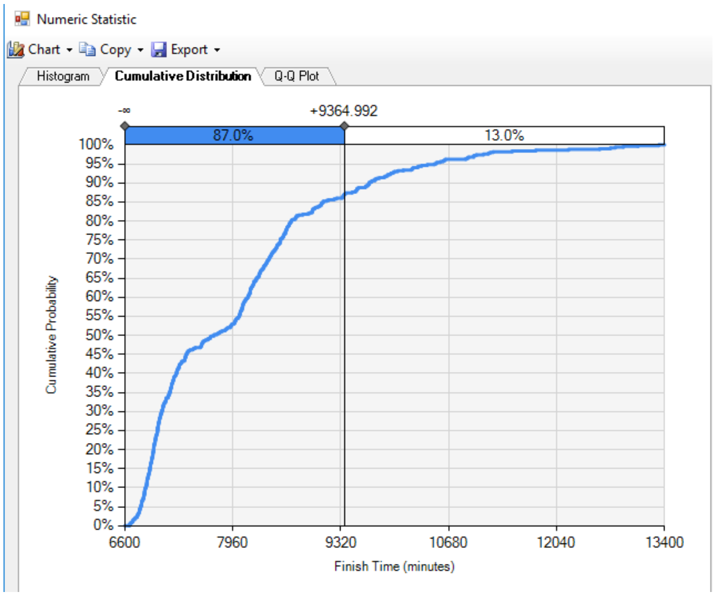

Figure 4: CDF of project duration.

From the CDF of project duration, it can be seen that 87% of the time the project duration calculated by the simulation model in 500 runs is between 6,600 minutes and 9,365 minutes.

5.2 Crane Utilization

There is only one crane used in this project, which an average utilization rate of 71.3%, with maximum utilization of 85.4%. The standard deviation of crane utilization is 6.3%. The crane is not 100% utilized due to modules transportation delays and weather constraints.

5.3 Crew and Space Utilization

The optimum number of crew members required to complete the project at the minimum duration and with the best utilization of the crane is 6 on the fitting crew and 4 on the welding crew. The average and maximum utilization of the fitting and welding crew is 53.4%, 63.5%, and 63.8%, 76.2%, respectively. The available space is 100% utilized.

6 VALIDATION AND VERIFICATION

Verification and validation of the model is very important for decision-making as it gives an idea about whether the model is behaving the way that was intended (Sargent 2010). There are many simulation tools in the industry and each tool has its own method for model verification and validation.

6.1 Verification

For this simulation model, trace log and counter are used for verification. The trace log is placed in the model to check the timing of the entity flowing in the model. Trace log assists in tracking the entry and exit time of the entity at a certain task; it also helps to check the availability of the crew and crane at a certain time and the results are found to be logical. The second method used for model verification is the placement of the counters in the model, which were helpful to confirm the number of entities expected to arrive at the location, the results of which are also consistent with the initial records.

6.2 Validation

For this simulation model, two validation methods are used for validation, namely "Extreme Condition Test" and "Historical data validation". So for the first validation method, the number of welding crew and fitting crew are set to "100" and "200" respectively for the simulation model. The final simulation results are shown in Table 4, which has a comparison with the normal setting. As can be seen from the comparison results, "6 fitting crew and 8 welding crew" is the best scenario in terms of project duration and cost while "100 fitting crew and 100 welding crew" set was proved to be a waste of manpower. But on the other hand, the total duration and crane utilization showed nearly no variation which supported that the simulation model is validated.

Table 4: Crew setting comparison.

Crew setting	Total duration	Crane utilization
2 fitting & 2 welding	13671	57.6%
4 fitting & 4 welding	10200	66.21%
6 fitting & 8 welding	8003	71.3%
10 fitting & 10 welding	8135	70.9%
100 fitting & 100 welding	8121	71.0%

For the second method which compared the simulation results with a similar project done in 2008 and with almost no consideration of the weather, the results are shown in Table 5. The utilization of equipment and manpower are relatively high for the similar project because of the absence of weather interruption which also proved the validity of this proposed simulation model.

Table 5: Resource Utilization Comparison.

	Utilization	
Resources	**Model**	**Model not considering transportation and weather delays**
Crane	71.3%	83.78%
Fitting Crew	53.4%	62.4%
Welding Crew	63.2%	59.17%
Space	100%	100%

7 CONCLUSION

Although the up-front work of modular construction takes place in a controlled environment, the uncertainties related to the modules' transportation and assembly processes could have a huge influence on the overall schedule by potentially increasing the project total duration as well as the budget. The simulation tool, Simphony.NET in this case, is able to model the whole process and provide a statistical result with a relatively high reference value. For this paper, the weather data was collected and combined into the model, which is fairly important since weather has potentially crucial impacts on construction. The results showed that there is an almost 7% duration delay if weather constraints are applied. As for the limitations of this research, weather issues could be potentially allocated more accurately. Instead of varying based on a specific cycle of 12 hours or 24 hours, the weather condition on site, wind force in particular, could change at any time. Therefore, the proposed method, which assumed that the weather Markov Chain changes its state every 24 hours, cannot restore the real world condition at the 100% level. Therefore, continuous simulation can be added to this model in the future to simulate the weather transformation, which is closer to the reality. Furthermore, the continuous simulation approach could also be used for the traffic delay part by incorporating the ArcGIS software. By analyzing the traffic flow data for each subsection in the route, the speed of the transportation vehicles, which could change continuously upon the time can be modeled. For future opportunities, this proposed model could be used for the comparison of different construction scenarios. If the contractor is focusing more on the project delivery time, then extra space can be developed for module storage and crane allocation. In addition, the lifting sequence could be changed to by floor instead of by each single house, then some procedures can be removed and the process will become more repetitive.

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