DISCRETE-EVENT SIMULATION MODEL FOR OFFSITE MANUFACTURING IN AUSTRALIA

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Offsite Manufacturing (OSM) has potential capabilities to enhance the Australian affordable housing supply. However, OSM supply chain requires effective management between two concurrent working sites: (1) offsite factory; and (2) building site. This means that information and material flows are necessary components for managing OSM supply chain. Nevertheless, the OSM supply chain is influenced by a number of major challenges such as broken junction between offsite and onsite, jumbled onsite process and vague customer demands. To overcome these challenges, this paper developed a Discrete-Event Simulation (DES) model for OSM in Australia. The Arena® software is designed to model manufacturing and construction processes to support a high level of analysis. Arena® provides advanced capabilities to mimic the behaviour of real system entities, layout and flow logic, as well as to produce data distributions and confidence intervals for the performance measures. The actual data was collected using interview with four OSM builders in Australia. The simulation model assist to evaluate three OSM scenarios (as-is, what-if I and what-if II) with different house order information intervention to the OSM supply chain. The simulation results indicated noteworthy improvements in the house completion time. Some limitations are acknowledged as the study reports on the findings using just limited interviews. Secondly, the model was developed and tested within Australia only; as such future studies could be employ case studies and further be conducted in other countries to enhance the generalisation of the findings. Currently, there are limited studies which seek to investigate the potential of DES within the housing supply chain management. In order to address this gap, this paper contributes by developing a DES for addressing challenges associated with the supply chain within the Australian housing sector.

Keywords: Arena® Simulation, discrete-event simulation, offsite manufacturing, modelling and simulation.

INTRODUCTION

The supply of affordable houses is an urgent concern for the housing market in developed countries (Demographia 2014). The Australian housing market is experiencing a severely unaffordable situation and the calls for affordable housing supply are increasing continuously. In such an environment, offsite manufacturing (OSM) has been suggested as one of the viable solutions to improve the housing affordability situation. OSM has the capability to meet the growing affordable housing demand by providing houses at reasonable price without compromising the quality (Mostafa *et al*. 2014a; NHSC 2013). OSM provides a factory controlled environment to fabricate house components (e.g. panels, pods, or modules). The house construction components are manufactured in the offsite factory then transferred to the building site for assembly and installation. The OSM practice accounts for 3%, with AUD 1.4 billion value of work, of the total construction sector in Australia (Schesinger 2014).

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Approximately, more than 54 corporations constitute the OSM industry in Australia working in non-volumetric and volumetric pre-assembly and modular building (Blismas and Wakefield 2009). OSM has been acquired a popularity from practitioners and researchers in Australia in recent years (Kenley *et al*. 2012; Mostafa *et al*. 2014b; Wynn *et al*. 2013). This is clearly from the establishment of PrefabAUS as the peak body for Australia's OSM industry in 2012. It comprises OSM manufacturers, suppliers, architects, engineers and research bodies whom are committed to innovation, productivity and quality in Australian built environment through an increased uptake of prefabricated building technologies (PrefabAUS 2015).

Simulation is a suitable tool for evaluating and analysing the dynamism of any system. It has been used in to model and evaluate different alternatives in complicated construction projects (AbouRizk 2010). Discrete event simulation (DES) is an effective technique to represent and study the operational processes of any construction system. In the UK, for example, Vidalakis *et al*. (2013) used DES to study the effects of varying demand of construction materials on logistics performance measures. In Australia, DES has been mainly used in specific areas of offsite supply chain including planning and scheduling of workers. Arashpour *et al*. (2015) applied DES to create multi-skilled resources in OSM through comparing cross-training strategies. Another study by Dalton *et al*. (2013) designed a simulation model for investigating relationship between day-to-day operational variations effect on the volume builders efficiency. The simulation model allowed explaining the behaviour of construction system used by the volume builders. At the same time, the extent of resource availability effect on house completion time was investigated by Fadjar *et al*. (2013). Their research showed that DES is an effective method to predict the effect of resource shortage on the house completion time.

Despite these research works, considering the entire OSM supply chain from receiving the house order until the completion of the house is insufficiently addressed. Most importantly, materials and information flows are important for an efficient OSM supply chain. This is because of the extended nature of OSM supply chain to manage two working locations concurrently and potential production process bottlenecks. Moreover, each house order has to run through many different processes once a builder received the order. Each OSM process is influenced by the availability of the resources and conditions at the building site. This leads to unpredictability of house completion time and delivery to clients. Therefore, this paper applied simulation to control the randomness of OSM processes and to evaluate different scenarios of house order interference within the OSM supply chain. The simulation model used was developed using Arena® simulation software.

RESEARCH METHODOLOGY

The objective of this research is to develop a conceptual model representing the entire OSM supply chain in Australia (As-is scenario), and suggest and test improvement scenarios (what-if) using simulation. The methodology in this research is based on discrete event simulation (DES) as suggested by Martinez (2010). The rationale and benefits for using DES over other simulation modelling techniques is well documented in literature as previously discussed in the preceding introductory section (AbouRizk, 2010; Vidalakis *et al*. 2013; Dalton *et al*. 2013; and Fadjar *et al*. 2013). Recent studies such as Moradi *et al*. (2015) further provide support to the appropriateness of DES by comparing it with systems dynamics across a number of criteria including problem scope and model components. Generally, DES has been applied at the operational level due to its capability to capture detailed information on the resources (operational details including availability, processing time, and idle time) and flow of entities (logic, probability distribution, queue and waiting). Arena® simulation software was used to model and evaluate different scenarios of the OSM supply chain. The stages of the research methodology are to:

1. Identify the main processes and stakeholders in the whole OSM supply chain
2. Develop the conceptual model for the entire OSM
3. Suggest and evaluate scenarios of managing OSM using DES

For data collection, this study employed literature reviews and interviews with OSM experts in Australia. A review of the related literature on OSM in Australia assisted in establishing a base of the OSM. This includes the types of OSM, OSM main processes and builders. This facilitated designing the interview questions. The interview was conducted to identify the key processes and its operational data within the current practice of OSM supply chain of a single-storey detached house as mentioned in Blismas (2007) with average floor area of 241.1 square meters as indicated in the Australian Bureau of Statistics (ABS 2014). The average floor area represents the median value of the usable space in a house at the final stage of its construction across Australian States and Territories (ABS 2014). Teddlie and Tashakkori (2009) stated that semi structured interviews facilitate the gaining of an insight to the research topic. Therefore, this study used semi-structured interview to facilitate open discussions on the OSM processes. The interviewees' organisations and contact details were identified from the member directories of PrefabAUS as well as help from the PrefabAUS CEO and founding director. The interviewees were recruited based on their direct involvements and experience on OSM processes (design, manufacture and building site). The total number of invitations sent for interview participations were 24. However, only seven participants' were willing to participate but, three participants later declined due to work and time commitments. Therefore, a total of four interviews in two different Australian States were conducted via telephone following the suggestion of Hughes (2008). The telephone interview is widely recognised as cost effective when interviewing participants across geographically dispersed area. The interview lasted between 30 to 60 minutes. Because of the small number of the conducted interviews, the data was transcribed and classified manually. The data covered the OSM processes and it operational characteristics including process time, and resources which are required for the simulation modelling.

OSM CONCEPTUAL MODEL

Form the literature review and interview, approximately 25 critical OSM processes identified for developing the conceptual model. Figure 1 demonstrates the material and information flows including as well as stakeholders including clients, subcontractors, and material suppliers.

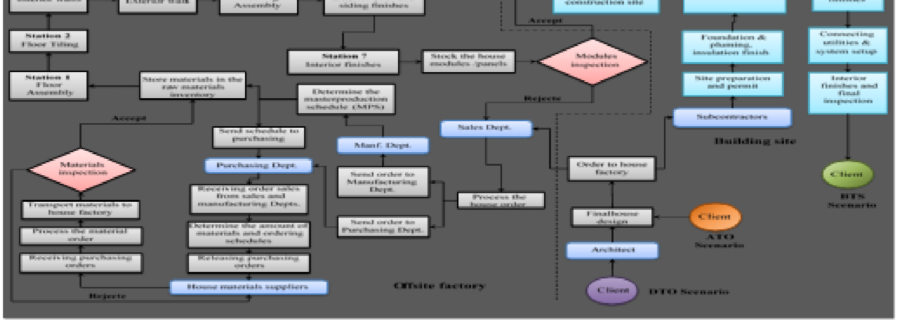

Figure 1: conceptual model and scenarios for OSM supply chain

The typical OSM information flow starts with the client-builder interaction to design the house. The potential client initiates the process by discussing the specifications of the house with the architect in order to finalise the house design. This is the current scenario (As-Is) of OSM in Australia and named design to order (DTO). When the design is approved by the client, the sales team prepare the house order and simultaneously communicates with the manufacturing supervisor for producing the components and the construction manager for preparing the building site. At the same time, the building permits are obtained from the housing council or developer. Then, the house order is sent to factory for production. In the factory, the manufacturing department defines the master production schedule (MPS) and what is required for purchasing. Accordingly, the house order is distributed to the floor, walls and roof production lines. The role of purchasing department in the offsite factory is to provide the necessary materials for house components manufacturing. This is done through preparing and releasing the materials orders to suppliers. Once the purchasing order received, the sales department employees inspect and store the materials in the raw materials inventory. When the house order components fabrication is finished, the components transported to the building site for installation. The components are uploaded and anchored on the building site once it arrived. Simultaneously with house components manufacturing, building site is prepared for installing and assembling the components. The preparation includes the excavation works, footer install, and foundation pluming and insulation finishes. After the components are assembled, the first fix started with finalising the external finishes and joining the utilities. Subsequently, the second fix of internal finishes and final inspection are completed and then the order is ready to handover to the client.

ARENA SIMULATION MODEL DESCRPTION

Model development

The conceptual model (Figure 1) was assured to represent the OSM supply chain. Then, the simulation model was developed to exhibit an overview of the current entire OSM supply chain and possibilities for efficiency improvements before implementation in the real world. This prevents a costly real world experiments. As the model is large and complex, the authors followed the suggestion of AbouRizk *et al*. (2011) by divide the model into four sub-models as demonstrated in Figure 2. These sub-models are: (1) finalising the house order; (2) preparation of the building site; (3) factory production of the house components; and (4) house installation.

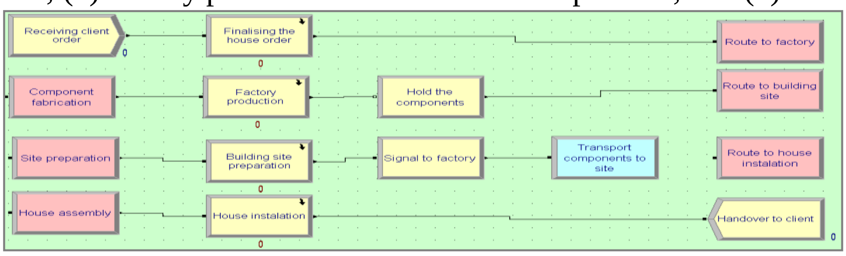

Figure 2: Arena simulation model of the OSM supply chain

The simulation model (see Figure 2) begins with the create module which is starting point for all entities in a simulation model in Arena® software (Kyu Choi and Kang 2013; Sadowski *et al*. 2007). The create module titled as receiving client order which makes an entity named as *"Ent Client"*. Consequently, the order goes through the four sub-models with different processes until they dispose at handover to client.

Simulation model assumption and runs

The model assumptions were determined by the real system operational conditions. In developing the simulation model using the Arena®, the following assumptions were used in this paper in the simulation of all four sub-models:

- The inter arrival time of client order in the first sub-model follow exponential distribution. It was assumed one order every five days and 2 entities per arrival with maximum 100 house order.
- The time probability distribution of the three sub-models was assumed to follow a triangular distribution. It is commonly used in situations where the minimum, maximum, and most likely values are available (Van der Aalst *et al*. 2010).
- Building materials were assumed to be available.

The simulation model was run over 36500 (356 days × 100 replications) working days. To approximate the number of required replications for the three scenarios, this paper followed the suggestion of Kelton *et al*. (2010). The first scenario, ATO, was simulated for an initial number of 20 replications. Then, the simulation runs for 100 replications which produced a 95% confidence interval. Each replication length was 365 calendar days with eight hours per day.

Model verification and validation

Model verification is done to ensure that the conceptual model is programmed correctly and does not contain errors or bugs while model validation ensures that the model meets represents the real system (Pace 2004; Shi 2002). In this paper, the authors considered the validity and verification of the conceptual and simulation models. The authors make sure that the conceptual model represents the real system of OSM through checking the model with the builders. Similarly, the Arena model has been verified through checking the logic and behaviour of the overall model and the four sub-models. Moreover, authors employed the independent verification and validation approach suggested by Sargent (2013). The authors contacted a third (independent) party to assess the model. The third party is a simulation consultant at the Simulation Modelling Services (SMS) Corporation in Australia. SMS is the certified partner of the Rockwell Automation (founder of Arena® Simulation) in Australasia. The simulation consultant reviewed the verification and validation of the simulation model developed. The consultant concluded that the model was an accurate demonstration of the OSM conceptual model.

RESULTS AND DISCUSSION

DTO (AS-IS) Scenario

This scenario covers most of the current practice of OSM in Australia. That is why the authors considered as-is scenario. In developing the simulation model, the authors identified the key performance measures that represent the OSM. The measures from a builder perspective are mainly related to the house completion time and number of orders they can achieved. House completion time is the total duration from receiving the house order until handover the house to a client. This time covers finalising the house order, components manufacturing time, building site preparation and components installation onsite. Therefore, all measures for these times and other such as record of house orders, finished houses in factory and completed house onsite were built in the Arena model using record module. This module continuously records the values for each measure over the whole simulation period (presented in Figure 3).

OSM Supply Chain Model

Replications: 100 Time Units: Days

User Specified

Tally

Between	Average	Half Width	Minimum Average	Maximum Average
Building site prep time	7.3335	0.02	6.0535	9.0775
Manufactruing time	14.3344	0.02	13.0439	16.2840
Record the completion time	26.3352	0.02	25.0567	28.2420

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
House orders in	67.7000	0.22	64.0000	71.0000
No of completed houses	53.1900	0.23	56.0000	63.0000
Record finished houses	63.6600	0.23	59.0000	67.0000

Figure 3: Arena simulation counter and tally results of the as-is scenario

It can be seen from Figure 3 that the house orders generated during the simulation time (almost 365 working days × 100 replications) were 71 orders. The finished manufacturing house orders were 67. This means that there are four house orders in the manufacturing process. The three time measures are also presented in Figure 3. The total duration from receiving the house order until client handover was approximately 29 days on maximum average. Moreover, the building site preparation time is nine days which included all site excavation, footers installation and foundation walls. At the same time, the manufacturing time of the house components was approximately 16 days. This consisted of all processes of the floor, roof and interior and exterior walls cutting and finishes.

What-if scenarios

The completion time is considered as one of the main factors of the housing undersupply situation in Australia (Dalton *et al*. 2013; Mostafa *et al*. 2014a). The house completion time can be shrink either by minimise the components manufacturing, the site preparation or house installation times. For this reason, this paper hypothesised and experimented two OSM (what-if) scenarios that highly contribute to house completion time reduction (presented in Figure 1). These scenarios are ATO and BTS. A brief description of each scenario is as following.

ATO (What-if I)

This scenario represents the situation where the client order interfere the OSM supply chain after the components have been produced (see Figure 1). The clients have flexibility to select from the builder's catalogue. The customers can add extra features to their own kitchen, bathrooms, external living area, as well as upgrade standard items such as windows and doors (Dalton *et al*. 2011). This scenario is suitable for most f detached house building in Australia. It requires using of standard components and builders to include variety of designs which can meet various demands. Theoretically, from client's perspective, the manufacturing time is zero as the components already produced and stored. However, there are time involved in terms of building site preparation and the house installation. These considerations were included in developing the simulation model of this scenario using Arena (Figure 4).

OSM Supply Chain Model

Replications: 100 Time Units: Days

User Specified

Tally

Between	Average	Half Width	Minimum Average	Maximum Average
Building site prep time	5.4752	0.06	3.8755	7.3545
Manufactruing time	7.3376	0.06	5.4961	10.2390
Record the completion time	13.2792	0.06	9.8884	16.3128

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
House orders in	151.50	3.55	116.00	200.00
No of completed houses	133.29	3.15	98.0000	173.00
Record finished houses	142.56	3.42	104.00	192.00

Figure 4: Arena simulation counter and tally results of the what-if I scenario

The house orders generated during the simulation were 200 orders. The finished manufacturing house orders were 192. This means that there are four house orders need to be processed in the factory. In addition, the total duration from receiving the house order until client handover was about 17 days on maximum average. The building site preparation and the manufacturing times were around 8 and 16 days.

BTS (What-if scenario II)

BTS scenario refers to the intervention of the client order after installing the house components onsite. This scenario is convenient for volume house building projects such as social housing (e.g. affordable housing program, nursing homes and retirement housing (South Australian Government, 2014). This means private and public sectors could ensure their capacity for achieving large accommodation projects for low and medium income groups. BTS is also known as speculative house which means that the house built according to the builder design. This means that the finalising the design and the order are almost very minimal. This has been considered in the model development and simulating the model of this scenario.

OSM Supply Chain Model

Replications: 100 Time Units: Days

User Specified

Tally

Between	Average	Half Width	Minimum Average	Maximum Average
Building site prep time	4.5745	0.06	3.6545	6.4317
Manufactruing time	8.5454	0.06	6.7074	11.7006
Record the completion time	11.5775	0.06	9.3428	16.2415

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
No of completed houses	130.31	2.95	92.0000	159.00
Record finished houses	136.60	3.21	98.0000	174.00

Figure 5: Arena simulation counter and tally results of the what-if II scenario

The simulation results of all measures in the three scenarios are listed in Table 1. It is clear that the house completion time is decreased to about 17 days (What-if I scenario). Compared with the as-is scenario results, the decrease is approximately 9 days in completion time. This result shows a significant improvement. Clearly, there is a notable decrease in the difference between the manufacturing time and building site preparation time. In what-if II scenario, the difference is around 4 days, however, the difference is 7 days in the as-is scenario. The difference could represent the time gap between the two sites (offsite factory and building site). This leads to waiting time (non-productive) and inventory costs in the factory.

Table 1: Summary of simulation run results of the three OSM scenarios

Average value	DTO (as-is)	ATO (what-if I)	BTS (what-if II)
Build site prep time	7.3 days	5.6 days	4.6 days
Manufacturing time	14.3 days	7.3 days	8.5 days
House completion time	26 days	16.3 days	16.2 days
House orders received	67.7	136	151.51
No of houses manufactured	53.19	136.6	142.56
Completed houses	63.66	128.31	133.29

IMPLICATIONS

This research responses to the proposed action plan of Blismas (2007) for realisation of the potential capabilities of OSM in Australia. This research considered the entire OSM supply chain from receiving an order to completing the order and handover houses to clients. This is one of the first studies in Australia to our knowledge in exploring the entire OSM system dynamics using DES. Three different scenarios (as-is, what-if I and what-if II) have been developed based on altering information intervention of a client order within the OSM supply chain and tested using DES. The simulation results (see Table 1) provide compelling evidence for practitioners for managing the OSM supply chain. Generally, the two what-if scenarios appear to be effective in reducing the house completion time and increasing the number of completed houses. Similarly, it demonstrates two configuration options for adjusting the OSM supply chain capacities in order to achieve high orders of completed houses. The conceptual and simulation models introduced in this study can give practitioners insights of redesigning OSM resources to match client demand with their capacity. Furthermore, DES using Arena® can help in evaluating different scenarios before real implementations with minimal expenditure. At the same time, Arena® as a DES platform can be used for training purposes in factories and building sites.

CONCLUSION

This study developed a discrete-event simulation model for the OSM supply chain in Australia using Arena® simulation software. The simulation model was constructed according to the conceptual model that represents the current practice (as-is) of OSM in Australia as demonstrated in Figure 1. The conceptual model shows the entire OSM supply chain (main processes and stakeholders) from receiving the house order until handover to the client. The conceptual model was developed and validated through interviewing four major OSM builders who are also members of PrefabAUS. As a result of this approach, it can be inferred that the model is an accurate representation of the actual OSM practice in Australia. Accordingly, the conceptual model was developed and programmed using Arena® interface software (see Figure 2). This has been done by using the basic process, advanced transfer and advanced transfer templates in Arena. The simulation model was verified and validated using independent verification and validation (IV&V) approach suggested by Sargent (2013). This approach involved a process where third party (Arena simulation consultant) reviewed the verification and validation of the simulation model to assure that it is a precise representation of the developed conceptual model. Therefore, three scenarios were simulated by modifying the client order information interference within the OSM supply chain. The as-is (DTO) scenario where the order received at the design process, while the what-if scenarios I and II (ATO and BTS) were based on receiving the order after manufacturing the house component offsite and after finishing installing the house respectively. The simulation results in term of the times measures and counting of orders received and completed were provided for each scenario (presented in Figures 3, 4 and 5).

The two what-if scenarios demonstrated in this study and their simulation results display the significance of the client order information in managing the OSM supply chain. Besides, the information flows amongst all stakeholders involved in delivering the house order. These scenarios showed noteworthy improvements in terms of building site preparation time, manufacturing time, and house completion time as well as the no of house orders completed. For affordable housing practitioners (OSM builders) and decision makers, the implication is that the discrete-event simulation model would enhance the supply of affordable housing, thereby contributing to the overall effectiveness of the offsite manufacturing process. Some limitations are acknowledged as the study reports on the findings using just limited interviews. The model was developed and tested within Australia OSM context (based on the assumptions mentioned earlier and for single-story detached house of 241.1 square meter floor area); as such future studies could employ case studies and further be conducted in other OSM contexts to enhance the generalisation of the findings. Moreover, other scenarios that focus on enhancing the OSM performance using the model provided are suggested for future research. Furthermore, future works can expand this study to cover other processes in the modular/OSM industry such as integrating manufacturing concepts including lean, agile and six sigma.

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