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Modelling, simulation and optimization of the materials flow of a multi-product assembling plant

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Abstract

Various dynamic factors impact the movement of materials within a manufacturing environment, increasingly becoming complex for multi-product assembling plants owing to the multiplicity and interconnectedness of these factors. Analyzing these factors can be equally complex, requiring modelling and simulation tools. This paper looks at the modelling and simulation of the materials flow of a multi-product furniture assembling plant to develop an efficient system that accomplishes timely product deliveries at minimal cost. Generic simulation models based on 2 products were developed and constructed using Arena® Simulation Software. Following the simulation experiments and implementation of the results, the average hourly throughput was significantly increased and additional space to store materials prior to processing at workstations was created. The generic models were compatible with the company's other products and hence useful for the company’s production planning and scheduling.

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Keywords: Arena®; materials flow; modelling; optimisation; simulation; workstation

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1. Introduction

The key objective of any manufacturing company is to maximize on profit margins, hence the production function of manufacturing companies holds the key to the success of these organizations [1]. The case study in this research is a furniture manufacturing and timber processing company in which production flows are characterized by many dynamic and complex factors which usually result from the unpredictable manner in which orders are placed let alone the dynamic flow of materials in the factory, often leading to the failure by the company to meet customer orders on time. This was evidenced by the variability of the average number of products produced per week over a period of 3 years from 2009 to 2012. Manufacturing companies have realized the need to invest in state-of-the-art and modern methods of manufacturing coupled with computer integrated manufacture for accuracy, consistence and repeatability [2]. Most indigenous owned manufacturing companies in Zimbabwe evidently lagged behind in the acquisition of modern equipment and systems owing to limitations in financial capacity. This was exacerbated by the global recession that affected many developed and emerging economies from around 2008, especially in Sub-Saharan Africa because of weak global linkages [3]. Local companies in Zimbabwe at that time focused on production, leaving very little or no funds for research or new techniques. In the absence of proper working systems and production schedules, a lot of the work was being carried out haphazardly, resulting in delays in meeting customer orders. Following an 'as-is-analysis', other problems identified included; old and obsolete equipment, thus creating bottlenecks in production, backtracking and crisscrossing of process flows, resulting in long distances travelled by parts and contributing to delays in production, hence costly products. Simulation models can be built to study the effectiveness of different forms of materials handling equipment by considering their detailed parameters such as speed, process paths and control logic. This paper looks at the modelling and simulation of the company's multi-product furniture manufacturing and assembling plant with the objective of appropriately scheduling production using the right product mixes and process flows through optimizing materials flow to accomplish timely product deliveries and thus achieve sustainable operations. Most simulation models are not generic but specific for each system that is being studied. Although the two models in this paper were developed for two products using a limited simulation software, they were generic in that only slight modifications were required in order to experiment on other products at the company.

2. Background to modelling and simulation

Models to be simulated can represent a real-world process more realistically because fewer restrictive assumptions are required [5]. Consequently, simulation provides a more realistic replication of the dynamic nature of the flow of materials within a factory rather than to rely completely on static analysis, which can be misleading in establishing a good system [6]. Production schedules, variation in product mixes, availability of materials handling equipment, and random breakdowns create varying loads on the system [4]. Static and dynamic analysis should both be utilized in evaluating the efficiency of a plant layout in terms of flow of materials for complete, accurate and timely analysis. More essentially, the simulation approach does not disrupt the on-going activities on the factory setup but it provides a problem identification and solving tool that is flexible and less costly than physical prototyping and experimentation. The approach also allows time compression, whereby simulation accomplishes in minutes what might require years of actual experimentation. One way of accomplishing timely product deliveries is through designing an efficient materials flow system by modelling and experimenting on product mixes depending on orders that would have been received and thus assisting in production scheduling. Modelling and simulation normally starts with the proper identification of the problem which entails specification of objectives and identification of the relevant controllable and uncontrollable variables of the system to be studied [7, 15]. Due to the nature and complexity of simulation to problem-solving, it should really be used as a last resort, after ascertaining that other approaches such as queuing theory cannot be used to solve the particular problem, a vital aspect in the initial stages of modelling and simulation. [8, 9]. The first step in constructing a simulation model is determining which properties of a real system should be fixed (parameters) and which should be allowed to vary throughout the simulation run (variables). Variables for models are specified by either of the two categories of distributions used for simulation; empirical frequency distributions and standard mathematical distributions. Such distributions have to be determined by direct observation or detailed analysis of records but other situations can reasonably be assumed to closely approximate a standard mathematical distribution such as normal or Poisson [10, 16]. The length of the simulation runs depend on the purpose of the simulation. The most common approach is to run the simulation for a set period, such as a month, to see if the conditions at the end of the period appear reasonable. Errors may arise in the program from mistakes in coding or in logic [11, 17]. The input data to a simulation model is obtained through work measurement and this includes process flows, distances between workstations, mode of materials handling and time to perform an operation [8]. Simulations are primarily concerned with experimentally predicting the behavior of a real system for the purposes of designing or modifying its behavior to achieve a certain purpose or solve a particular problem [12]. In conducting a simulation experiment, values for the controllable inputs are selected and values for probabilistic inputs are randomly generated. Based on these values, the model is then used to compute the values of the output [13]. However, simulation is not an optimization technique but a tool that can be used to predict how a system will operate given certain conditions for the controllable inputs and randomly generated values for the probabilistic inputs [14]. Quantitative analyses often make use of simulation to determine values for the controllable inputs that are likely to tend towards desirable outputs, in which case, simulation can be an effective tool for designing systems to provide good performance. Depending on the simulation results, attempting additional runs on the experiments may be ideal and this can be achieved by changing factors such as parameters, variables, decision rules, starting conditions and run length [2].

3. Case study and methodology

The case study company specializes in mid-volume or batch production and assembly of domestic and commercial furniture as well as industrial timber products. In selecting the products for use in the modelling and simulation research and eventual construction of the generic simulation models, consideration was given for those products that went through most of the workstations as well as being representative of the manufacturing processes at the company. Pallets were chosen to represent the generic simulation model for industrial timber products while baby tenders were chosen to represent the generic simulation model for domestic furniture. Fig. 1(b) illustrates the ten stage material flow for baby tenders in which the flow starts with the arrival of raw timber in the timber yard, hereinafter Workstation 1 (WS1) followed by the selection of suitable timber for the various parts of the baby tenders before being ferried through 54m to the surfacer (WS2) for planing and throughout the illustrated stages until WS10. Pallets go through an almost similar but shorter process as shown in Fig. 1(a).

3.1. Process flows

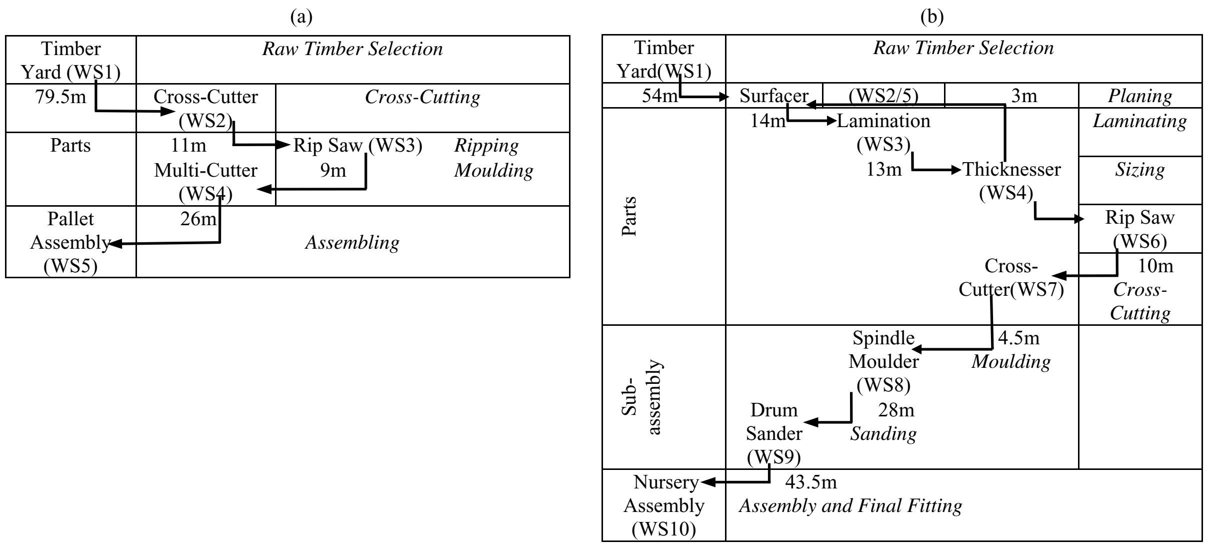


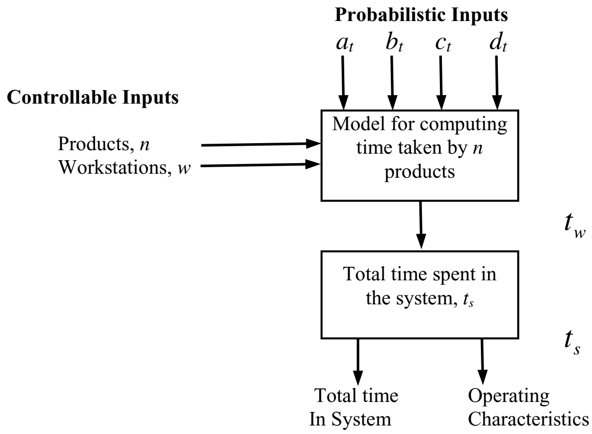
Fig. 1. (a) Five stage process flow for pallets; (b). Ten stage process flow for baby tenders

3.2. Mathematical model

The generic simulation models for both the pallets and baby tenders were developed based on Figs. 1(a) and (b) in conjunction with the materials flowchart using Arena® Simulation Software. The 4 time parameters used were:

- a_t material movement time from previous workstation to active workstation.
- b_t waiting time before being processed at the active workstation.
- c_t product processing time at the active workstation.
- d_t waiting time after processing before moving to the next workstation

The size of a component or product is an important consideration in assembly line analysis and design because the number of products that can be handled at each workstation affects worker performance. Hence the number of products *n,* entering the assembly line at a given time should not exceed a certain value and thus *n* became one of the controllable inputs to the simulation model while the other were the number of workstations, *w*. The probabilistic inputs to the materials flow simulation model were the 4 durations, a_t, b_t, c_t and d_t derived from data collection and analysis at the same plant [19]. The output consisted of various operating characteristics such as average queueing time, hourly output and the total time spent in the assembly line as shown in Fig. 2 along with equations (1) and (2) for the computation of total time spent at a workstation, t_w and in the system t_s. After developing the general simulation model outlining the inputs and outputs of the model, this was extrapolated further into developing the materials flow chart which defined the sequence of logical and mathematical operations required to simulate the materials flow for pallets and baby tenders, taking note of the appropriate processing, idle and movement times.



$$t_w = \sum_{x=1}^{n} (a_t + b_t + c_t + d_t)x \tag{1}$$

$$t_s = \sum_{w=1}^{s} t_w \tag{2}$$

Fig. 2. General simulation model for an *s*-stage flow line.

Owing to the complexity of real production processes, a number of assumptions were made prior to developing the models to provide a representative picture of the operations and outcomes. These included, two continuous 8 hour shifts in a day with minimal or no breakdowns, assuming machines would run uninterrupted and any maintenance or breakdown attended to during the off-shift periods. However in reality this may not be possible as machines can breakdown at any time. The models also assumed that orders received from retailers follow a uniform pattern based on previous sales history [21]. Due to scarcity of broad data, more experiments were required for validation.

3.3. Machine operating characteristics and parameters of the models

Workstations, process and assembly lines were identified as standard features of the generic simulation models. The flow system consisted of a number of workstations, five for the pallets and ten for the baby tenders. In addition, each workstation had two important resources; a machine to perform a task and a storage space to store components prior to processing. Each machine was assigned 4 possible states namely; starved (idle), busy (processing), blocked (storage space full) or failed (broken down). In the constructed models, the failure state was a function of a machine's average uptime and downtime percentages. The failure state was dependent on the company's breakdown maintenance strategy. The storage space capacity for each workstation was also assigned three possible states namely; empty, partially full or full capacity. Upon arrival at a workstation the components were delayed by a duration of time specified by a standard mathematical distribution, equivalent to the waiting time before processing. After processing, the material was delayed before being transported to the next workstation, depending on the status of the next workstation and this was also specified by a standard mathematical distribution. Four parameters identified and used in the two simulation models were; machine capacity (parts that can be handled at a time), storage space capacity for each workstation, total number of workstations in each model and machine uptime and downtime percentages. These are shown in Tables 1(a) and (b).

Table 1. Parameters for the simulation models (a) industrial – pallets; (b) domestic – baby tenders

(a)

Work Station	Machine Capacity	Uptime %	Downtime %	Workstation Capacity (Parts / Workstation)
WS1	1	100	0	24
WS2	1	75	25	24
WS3	1	75	25	24
WS4	1	80	20	24
WS5	1	100	00	8

(b)

Work Station	Machine Capacity	Uptime %	Downtime %	Workstation Capacity (Parts / Workstation)
WS1	1	100	0	16
WS2	1	75	25	12
WS3	1	100	0	12
WS4	1	70	30	8
WS5	1	75	25	12
WS6	1	80	20	10
WS7	1	65	35	10
WS8	1	70	30	18
WS9	1	60	40	14
WS10	1	100	0	8

3.4. Variables, verification and validation of the simulation models

The variables for the simulation models were obtained from previous work on data collection and statistical data analysis in conjunction with optimization of the plant layout and materials handling system of the plant [19, 20]. These variables were custom built probability distributions of the various time periods that characterized materials flow for the pallets and baby tenders and as defined in section 3.2. The probability distributions with their shape parameters for the Gamma (γ), Beta (β), Normal (η) and Uniform (μ) distributions and the mean for the Exponential (ε) distribution (in braces) for these durations are shown in Tables 2(a) and (b). A warm up period of about 3600 seconds was used as the starting condition for both models to discard any bias in the initial phases of the simulation run. The approach adopted in running the program was to perform the simulations continuously until an equilibrium condition was achieved when there were minimal variations in output results. The number of observations required to attain equilibrium were set in the simulation programs as the terminating conditions of the simulation runs, the run length being determined by the duration required to achieve an equilibrium.

Table 2. Variables and their probability distributions for the simulation models; (a) industrial – pallets; (b) domestic – baby tenders

(a)

Work Station	a_t	b_t	c_t	d_t
WS1	-	-	γ{3,1}	β{0.0,8}
WS2	ε{23.03}	Β{3,1.5}	γ{3,1}	β{2,0.8}
WS3	ε{14.95}	γ{3,1}	γ{3,1}	β{1.5,3}
WS4	ε{114.15}	γ{3,1}	β{3,1.5}	γ{3.1}
WS5	β{2,0.8}	γ{3,1}	ε{271.8}	γ{3,1}

(b)

Work Station	a_t	b_t	c_t	d_t
WS1	-	-	γ{3,1}	γ{2,1}
WS2	γ{3,1}	β{1,2}	γ{2,1}	γ{2,1}
WS3	β{3,1.5}	β{3,1.5}	γ{3,1}	β{2,2}
WS4	γ{3,1}	γ{2,1}	β{3,1.5}	β{3,1.5}
WS5	β{2,0.8}	ε{213.88}	β{1.5,3}	ε{262.329}
WS6	γ{3,1}	β{1.5,3}	γ{2,1}	γ{3,1}
WS7	β{3,1.5}	β{3,1.5}	γ{3,1}	β{3,1.5}
WS8	η{52.8,1.5}	γ{3,1}	γ{3,1}	μ{16.5,313.2}
WS9	γ{3,1}	β{1,1}	γ{3,1}	β{3,1.5}
WS10	γ{3,1}	γ{3,1}	β{3,1.5}	β{3,1.5}

Verification and validation were carried out to check whether the models were a valid translation of the flowchart and representative of the factory's materials flow. Challenges encountered included mistakes in coding by trying to run the program and let the computer review the errors for correction. This was resolved by splitting the program into small sections, followed by checking the validity of each section. Quantitative results from the models were compared with the raw data collected from the factory to verify the validity of each model. The experience gathered during the 'as-is-analysis' at the plant and the knowledge of operations for the company assisted a great deal and played a major part in the validation process. In a related research, probability distributions were obtained for the company's four main products of which results derived for bunk beds and baby tenders were used as input to the generic simulation models for this paper [19]. The sample sizes were initially an average of 25 readings recorded through each workstation in an hour and this figure increased slightly to 37 per hour after implementing recommendations on product mixes from this research. The validity of the models gave management an appreciable level of confidence because of the fairly reasonable representation of the real system based on the data and probability distributions. Fig. 3 (a) and (b) show snapshots of the generic simulation models for pallets and baby tenders developed in Arena®.

(a) (b)

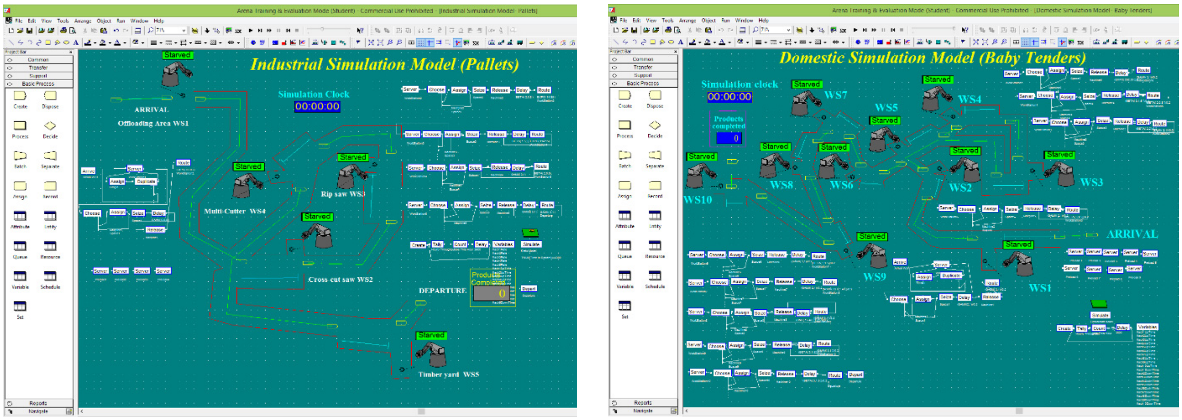


Fig. 3. Snapshots of the simulation models in Arena® (a) industrial model - pallets; (b) domestic model - baby tenders).

4. Results

Qualitative results were obtained from the direct observation of materials flow in the generic models through which flow bottlenecks were revealed as well as those workstations which were mainly; starved, busy, with large queues or with high frequencies of breakdowns. The generic simulation model for pallets showed that there were queues of materials at all workstations, with the largest occurring at WS2, WS3 and WS5 while shorter queues were observed at WS1 and WS4. Machines at WS2 and WS3 failed more frequently while those at WS1 and WS5 hardly experienced any failure. The generic simulation model for baby tenders showed that there were large queues at WS1, WS2, WS3 and WS4 while WS5 had a relatively shorter queue and no queues at all at the other 5 workstations. Machines at WS2, WS6, WS7, WS8 and WS9 were observed to have the highest frequency of breakdowns. These observations and qualitative results were useful to advise the company on issues such as, the use of preventive maintenance on those machines that frequently broke down, consider investing in additional machines to augment those that had large queues or disposal of old machines that frequently broke down and thus delaying production.

Quantitative results were an output from the simulation models which showed the average time spent by a product in the system, average hourly throughput and average times spent by machines being starved, busy, blocked or broken down (failed). The results gave the average times spent during production with the storage space being empty, partially full or full. Tables 3 (a) and (b) show the qualitative results extracted from the Arena® simulation outputs for the pallets and baby tenders respectively. The qualitative results tally with the quantitative observations indicating some validity of the models. The quantitative and qualitative results from both models formed a good basis for which optimization of the materials flow system was accomplished.

Table 3. Average queue times for (a) industrial – pallets; (b) domestic – baby tenders

(a)

Work Station	Average Queue Time (Sec)	Minimum Value (Sec)	Maximum Value (Sec)
WS1	4245.6	3754.2	19529
WS2	2624.6	404.3	6396.76
WS3	2635.6	484.59	6422
WS4	2005.5	1765.3	8904.6
WS5	2648.8	485	6453.1

(b)

Work Station	Average Queue Time (Sec)	Minimum Value (Sec)	Maximum Value (Sec)
WS1	1136.9	259.89	2767.2
WS2	2243	893.51	3557.2
WS3	1686.9	509.06	3557.2
WS4	1675.7	499.59	3566.9
WS5	65.294	0	1286.9
WS6	4.909	0	179.36
WS7	15.7	0	213.77
WS8	12.306	0	209.39
WS9	20.059	0	358.05
WS10	0.0518	0	6.6705

5. Discussion and recommendations

The approach taken in optimizing the materials flow system for the company was based on the results obtained from the two generic simulation models. Emphasis was placed on reducing the time spent by a product in the system to improve the system's hourly throughput. Averages times for; product at a workstation, machines in all states, queueing and a workstation's space being empty, partially full or full were employed to establish an optimal materials flow system. Results from the industrial simulation model showed that most of the production time and queueing was at WS5 which was busy most of the time. Thus attention was needed at WS5 to ensure that the hourly throughput was increased. This was probably because it was an assembly area where most of the work was carried out manually and recommendations were made to automate the processes. Results from the domestic simulation model showed that most of the production time was spent in the first 5 workstations where large queues were observed. This was attributed to the slow pace at which WS5 operated, resulting in materials from WS4 being blocked, filtering down to WS3 and so on. Additional machines were added at WS5 but it only improved the flow slightly as the throughput increased by only one product, hence it would not be cost effective. Further analysis and experimentation showed that in general, workstations 1-5 were much slower than anticipated. An identical block of machines was introduced to process materials in parallel with machines at workstations 1-5 resulting in sufficient supplies of materials to workstations 6-10 to prevent starving. Another option pursued was the creation of additional storage at workstations that had large queues to prevent blockage of flow from downstream workstations. This minimized the frequencies at which upstream workstations blocked materials from downstream ones, resulting in the average hourly throughput from 25 to 37 products while the average time spent by products in the queue decreased to 8541 from 10033 seconds. The average hourly throughput was also increased significantly by doubling the number of workers in the assembly area.

Analysis by simulation and modelling showed that the company could turn around its fortunes and increase its product throughput by reorganizing the process flows and thus fulfilling customer orders on time and ultimately result in sustainable operations and company growth. Implementation of the results from this research also meant that the company no longer resorted to the costly option of employing workers overtime. The simulation models constructed in this research were made flexible for extension to other products. This allowed the company to analyse and validate new products prior to launching them. The simulation approach used in this research has advantages of not only improving the materials flow but also to experiment on a real system without disrupting the ongoing activities in the factory. It therefore provided a fairly reasonable measure for predicting performance and planning for production through experimenting on what-if scenarios which were used to decide on product mixes, what products and when to produce them. The constructed simulation models also improved the company's throughput for the company to realize other benefits such as; reduced lead times, better utilization of space, equipment and machines and reduction in work in process. However, the models were limited in size and in some instances had to be broken down because of the limited version used. While this approach provided the company with a low cost option for planning and prediction compared to physical experimentation, there were a number of assumptions made as highlighted in section 3.2, which not only presented challenges for validation and verification but also some level of doubt in management confidence to embrace the technology. Future work was recommended with a commercial version of Arena® that can handle higher volumes of data and larger models.

6. Conclusions

Two fairly robust and generic simulation models were developed for the case study company's main operations in domestic furniture and industrial timber products. The constructed models were useful in optimizing the materials flow for the company. Implementing some of the recommendations such as introducing parallel machine blocks, additional workers in the manual assembly areas as well as creating additional storage space for materials prior to processing helped in the flow of materials among workstations and the average hourly throughput was significantly increased. The results from the research were welcomed by management and implemented immediately especially in view of the fact that the options did not require capital investment in machinery but just competent systems analysis in the use of the developed generic simulation models. The company managed to meet the demand for the company's main products of the pallets and baby tenders, delivering orders on time. The benefits realized from this research could be invested in acquiring the commercial version of Arena® or other simulation software, additional machines for the slow workstations and automating the manual assembly operations.

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