Process Mapping, Modelling and Optimization of Plant Layouts and Materials Handling in Manufacturing

W. R. Nyemba

Department of Mechanical Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, Auckland Park Campus, P O Box 524 Auckland Park 2006, Johannesburg, South Africa
E-mail: nyemba@yahoo.com
www.uj.ac.za

C. Mbohwa

Professor of Sustainability Engineering, Department of Quality and Operations Management & Vice Dean for Research and Innovation, Faculty of Engineering and the Built Environment, University of Johannesburg, Auckland Park 2006, Johannesburg, South Africa
E-mail: cmbohwa@uj.ac.za

L. E. N. Nyemba

Production Engineering Institute, Scientific Industrial Research and Development Centre, 1574 Alpes Road, Hatcliffe, Harare Zimbabwe
E-mail: lennyemba@gmail.com

Documenting process flows in a manufacturing environment provides a guide to understanding how processes are interconnected and how materials are handled, thus forming the basis for modelling and optimization in order to simplify the otherwise complex systems particularly in multi-product manufacturing. Research was carried out at a furniture manufacturing company specializing in the production of a wide range of furniture from hardwood. Owing to the multiplicity of processes and the movement of materials in manufacturing environments, the factors affecting such setups increasingly become complex, equally requiring complex techniques to analyze and optimize them. A work study carried out at the company established inherent problems that affected production and were used as the basis for modelling and optimizing the processes, focusing on grouping of workstations depending on functions, predicting performance using simulation and machine distance matrices for a reorganized plant layout. Results obtained after modelling and optimizing the plant layout were useful for production planning and control as well as enhancing the company's productivity and efficiency.

Keywords: Manufacturing; Materials handling; Modelling; Optimization; Process mapping

1. Introduction

This book chapter is an extended version of published research from conference proceedings and ongoing research on the modelling, simulation and optimization of the plant layout and process flows of a furniture manufacturing company in Harare, Zimbabwe, specializing in the production of a wide range of domestic, industrial and commercial furniture from hardwood [1, 2]. Businesses are established to generate profit and to achieve good profits, the key objectives are the maximization of yield and efficiency while minimizing operational costs [5]. Process mapping involves the documentation of process flows by distinguishing how work is actually done from how it should be done, what functions a system should perform from how the system is built to perform [3].

This research was motivated by the global financial crisis that affected many countries around the world in 2008 [6]. Due to weak linkages between Southern African countries and those from the West, many thought the crisis would not affect countries in the region but because of the heavy reliance on foreign aid from developed countries, the effects had a toll on most of the developing countries in Southern Africa. Manufacturing companies in Zimbabwe were downsized and some were liquidated and in the same year, the country recorded the second highest hyperinflation in the world ever [7], leading to low capacity utilization in most manufacturing firms and eventually abandoning its own currency in 2009 and adopting multiple currencies [8]. Although this provided relief to manufacturers, it was short-lived as the country witnessed a rapid increase in imports at an annualized rate of 13.2% from 2009 to 2014, with a rapid widening of the trade balance during that period [9]. The use of multiple currencies was evidently not sustainable as the country soon faced liquidity challenges that resulted in the introduction of bond notes in 2016 to address the liquidity crisis [10]. However, this also did not resolve the crisis as the bond notes were in short supply and could not be used to import required spare parts for machinery [11].

The researchers were engaged by the furniture manufacturing company to propose ways in which the company can contain operational costs while improving efficiency and productivity to remain in business. This was a challenging task owing to the difficult operating environment which did not leave many choices to pursue under the circumstances. The research aimed at mapping and optimizing the process flows and layout of workstations within the plant through 4 objectives of machine distance matrices to reduce the amount of backtracking, materials handling techniques and equipment to allow for easy flow of parts, grouping of related workstations by functions and simulation using Arena to predict performance and enhance production scheduling and planning.

2. Review of Process Mapping and Optimization Literature

Several techniques have been developed over the years to address challenges encountered in manufacturing environments, all aimed at improving efficiency and enhancing productivity at minimal operating costs. The use of ProModel in modelling and simulation for a Just-In-Time (JIT) optimization of automotive components manufacturing, demonstrated that variables such as inconsistent task distribution, variations in operator performances, inadequacies in eliminating workstation set-up times and failure to comprehend Total Quality Management (TQM) principles, often disrupt desirable JIT production leading to low productivity and inefficiencies and hence reduced profitability [12]. Such techniques have become part and parcel of organized manufacturing environments of large corporates but to a less extent in small to medium enterprises due to limited capacities [13]. A basic tenet that forms the foundation for agile manufacturing is the need for relevant supporting production and operating systems and the company's ability to produce customized products at reasonable cost within the shortest possible lead times [14]. Although this research focused on the furniture manufacturing plant as a case study, the model was developed in a generic manner by experimenting on the company's other subsidiaries in such a way that the developed principles could be suited to other manufacturing companies in the same trade.

The design and arrangement of machines in a plant significantly impact the flow of materials within the plant and thus the total distances travelled during production. The arrangement of machines determine the structural complexity by virtue of the design and configuration [15]. Manufacturing companies involved in multi-product manufacture and assembly, operate in very dynamic environments, the complexity and uncertainty of which is driven by customer demands, product design and aesthetics, methods of production and general market conditions [4]. Six complexity indices based on the physical and structural attributes of the plant layout were used to develop a Layout Complexity Index (LCI) which enabled and facilitated the design of systems with the least complexity and hence were able to compare alternative layouts [15]. Modern machinery has evolved with time and in the process introduced added dimensions of complexity, requiring well planned platforms to enhance manufacturing flexibility. Small to medium enterprises in the developing world sometimes have to cope with conventional machines, that require even more stringent planning to cope with the production demands. The objective in any facility layout or optimization is to minimize material flow costs by reducing the distances travelled by materials, parts or sub-assemblies through mapping and appropriately positioning equipment in the plant [16].

Analyzing processes using simulation provides a realistic representation of the dynamic and complex nature of materials flow as opposed to relying entirely on static analysis [17]. Varying loads on a dynamic system are a result of production schedules, product mixes, materials handling equipment and random breakdowns [18]. More importantly, simulation does not disturb on-going activities but in fact it is derived from live data during processing, the results of which are used to predict performance and identify bottlenecks in the real system. Modelling and ultimately simulation requires proper identification of problems to ascertain relevant controllable and uncontrollable variables [19]. However, owing to the time taken in the proper modelling of systems, simulation should really be used as a last resort for optimization after other simpler techniques such as queueing theory have been tried [20]. In this research, simulation was used to complement the other techniques. It is crucial at the onset of simulation to determine fixed and variable parameters, the latter of which uses empirical frequency or standard mathematical distributions determined by direct observation of a running system. The data used in modelling and simulation is derived from operating systems by measuring flows, distances between workstations, mode of materials handling and time to perform operations. Values for the controllable inputs are selected and those for probabilistic inputs are randomly generated. Although simulation aids in predicting the performance of systems under given conditions, it is not an optimization technique [21], hence the approach in this research to use a cocktail of techniques that will lead to optimization. The layout and designs of factories require planning and optimum arrangement of workstations and facilities including personnel, storage space, materials handling and movement through product, process or fixed position layouts [22]. Generally, optimization involves finding alternative ways of production with the most cost effective performance under given constraints by maximizing desired factors and minimizing undesirable ones [23].

During the initial phase of this research, a number of problems that contributed to the overall product and operational costs ranged from conventional machines that broke down frequently, failure to meet customer orders on time, crisscrossing of process paths resulting in longer than necessary distances travelled by parts and manual materials handling and assembling. Based on these challenges, the research set out to answer questions ranging from what technical and social issues contributed to delays in production, what impact the location of workstations had on productivity and process efficiency and how machine distance matrices and functional groups in conjunction with modelling and simulation can help to resolve these challenges and what the financial implications are.

3. Methodology and Detailed Case Study

The case study company was a typical small to medium enterprise consisting of several divisions, with the focus for this research on 2 of the larger divisions specializing in the production of nursery furniture such as bunk beds and baby cots while the other specialized in cable drums and roof trusses. A detailed 'As-Is-Analysis' was carried out by observation and scrutiny of available documentation, skills and expertise in each division.

3.1. *Plant Layout*

Detailed measurements of the factory, positions of workstations, available space and flow of materials, parts and sub-assemblies were made and modelled used AutoCAD as shown in Fig. 1, with the various numbered workstations. Concurrently, data on products and sales trends, workstation locations and service distributions, materials handling equipment process paths, storage space as well as processing, idle and transportation times was collected. The work study also identified obsolete and dangerous workstations, crisscrossing flows, regions of interference, bottlenecks and potential candidate areas for plant layout redesign. The minimum distance travelled technique approximated the cost per unit meter using the average speed of transportation as well as the average wage for artisans. The layout of workstations at the inception of the research evidently showed backtracking and crisscrossing of process flows, contributing to long distances travelled by parts and interference and safety issues as evidenced by the process paths for the production of bunk beds shown in Fig. 1.

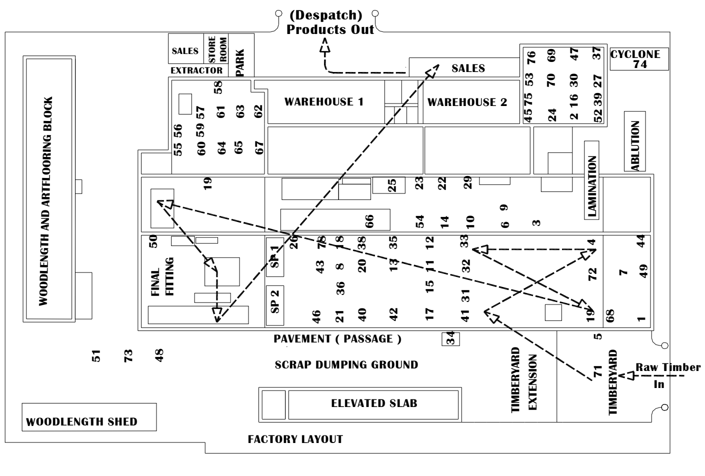

Fig. 1. Factory layout of the case study company at inception showing process flow for bunk beds.

3.2. *Production Planning*

For production planning and layout, analysis was done through observing production sequences, bottleneck workstations, limitations, constraints as well as targets and opportunities for redesign. Available space and the location of service facilities such as power points and outlets to dispatch were also taken into consideration. Analysis of these factors showed that available space was limited purportedly due to a number of obsolete machines that the company still kept within the factory as well as obsolete inventory and faulty machines awaiting repair. Modern and efficient materials requirements planning is essential to ensure that the right materials are procured at the right time and in the right quantities for JIT optimization [12, 24].

3.3. *Operational Activities*

The operational activities in a manufacturing environment are equally critical as the layout and scheduling as they are also useful for analyzing and optimizing production layouts and redesigns [25]. At the onset of production, machines are prepared and set up by regularly checking to ensure that products are consistent and of high quality. However it was observed that these procedures were not documented but based on experience and institutional memory. In addition to old and conventional machines, it was also observed that a number of these had faulty gauges or unstable mountings. Overloading of the machines, mainly due to lack of proper production scheduling also contributed to delays in processing and hence the high values of idle times. Inconsistent and low quality products owing to the use of cutting tools being used beyond replacement resulted in reworks and thus increased operational costs because of the additional need for polishing before dispatch. Most of the identified shortfalls simply required reorganization except for the old and conventional machines that obviously needed replacement.

3.4. *Mathematical Model*

The generic simulation model was developed for the bunk beds based on the process flows shown on Fig. 1 in conjunction with the materials flowchart using Arena Simulation Software. The four time parameters used in the model were:

a_t : Movement time from previous workstation to active workstation.
b_t : Waiting/idle time before processing at active workstation.
c_t : Processing time at the active workstation.
d_t : Waiting/idle time after processing and before moving to next workstation

To avoid overloading and high idle times, the number of products, n entering an assembly line should not exceed a stipulated value, hence n was used as one of the controllable inputs while the other were the number of workstations, w. The probabilistic inputs were the four time parameters, a_t, b_t, c_t and d_t, derived from the data collected at the same plant [2], while the output was average queueing time, production throughput and total time spent by parts in the system as shown in Fig. 2. Equations (1) and (2) were used to compute the time spent at a workstation, w_t and time spent in the system s_t. The developed simulation model was extrapolated to further develop the materials flowchart in order to define the order and sequence of mathematical operations required for the simulation.

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

$$S_t = \sum_{w=1}^{s} w_t \qquad (2)$$

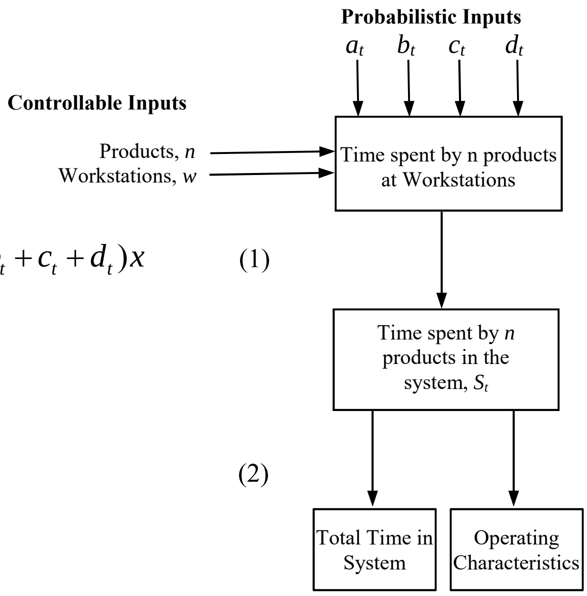

Fig. 2. Mathematical and simulation model for an *s*-stage process line.

A number of assumptions were made prior to developing the model including; 2 continuous 8 hour shifts in a day with minimal breakdowns and that any repairs to the workstations will be done outside the two shifts. Customer orders that prompt production were also assumed to follow a uniform pattern based on previous sales trends [26]. However in reality these assumptions may not be practical since machines can breakdown at any time and customer orders may vary from time to time. Nevertheless the assumptions were useful parameters for developing the simulation model.

4. Results and Optimization of the Plant Layout

The main objective of optimizing plant and production layouts in manufacturing is to improve productivity, enhance operational efficiencies in order to reduce product costs, thereby providing competitively priced products [27]. This research used a combination of 3 techniques, namely machine distance matrices, functional groups and simulation through analyzing the movement of materials, reducing transportation distances and reorganizing the positions of workstations in line with the functions in order to reduce the amount of backtracking of process paths.

4.1. *Functional Grouping and Materials Handling*

Most of the parts and sub-assemblies in the furniture manufacturing company were moved by forklifts, trolleys or by hand. Forklifts are mainly used for heavy parts such as those for kitchen furniture and coffins. The smaller components, usually after crosscutting to shorter lengths are transported by trolleys. Most of the processing is done in batches based on customer orders at any given time, an example of which is the bill of materials for bunk beds as shown in Table 1.

Table 1. Bill of materials for bunk beds

Part Number	Part Name	Quantity	Final Size	Rough Size
1	Slates	28	944 x 70 x 22	970 x 76 x 25
2	Cleats	4	1880 x 35 x 22	1905 x 38 x 25
3	Long Rails	6	1950 x 140 x 22	1975 x 145 x 22
4	Short Rails	8	970 x 140 x 22	995 x 145 x 22
5	Guide Rails	1	1950 x 100 x 22	1975 x 105 x 25
6	Legs	8	725 x 45 x 45	750 x 50 x 50
7	Dowels	4	L x ϕ 20	L x ϕ 25
8	Legs	2	1250 x 45 x 22	1275 x 50 x 25
9	Steps	4	260 x 45 x 22	285 x 50 x 25

The data gathered at the inception of the research focused on the three categories of materials handling equipment, i.e. forklifts, carts or trolleys for the optimal movement of parts and sub-assemblies within the plant while maintaining a smooth and continuous flow of materials. Although the forklift was the most ideal form of transportation, at the time of carrying out the research the country faced a shortage of fuel, trolleys and carts were mainly used for transportation, hence the need to relocate workstations such as the crosscut (41) an ripsaw (1) as close as possible to the timber yard. The coffins divisions was a relatively small section compared to the rest, hence the distances moved by parts were short and thus can be accomplished by hand except where large components are transported.

4.2. *Machine Distance Matrices*

Integration of the materials flow and handling equipment were used to determine the movement of materials between interacting workstations in order to reduce the distances travelled. A comparison was made for the number of movements between interacting workstations and the total distance travelled using the example of bunk beds as shown in Tables 2 and 3 from the Timber Yard (TY) through the corresponding Workstations (WS) to the final Assembling (Assy) area in the processing of short rails and slates for bunk beds. The total distance travelled by the short rails and slates is the sum of the distances travelled by these components, also referred to as the index of direct materials handling.

Table 2. Movements between workstations in the assembly of short rails and slates for bunk beds

	Short Rails Assembly							Slates Assembly			
WS	1	4	8	16	20	35	**WS**	41	4	15	21
TY	1						TY	1			
41	1	5					1	9	9		
7		7	7				7		19		
12			7	7	7	7	12		19	13	
13				7	7		35			13	13
Assy						7	Assy				21

Table 3. Total distance travelled by short rails and slates in the assembly of bunk beds

	Short Rails Assembly							Slates Assembly			
WS	**1**	**4**	**8**	**16**	**20**	**35**	**WS**	**41**	**4**	**15**	**21**
TY	15						TY	16.4			
41	12.8	115					1	239.6	96.5		
7		39.6	48.8				7		100.6		
12			39.6	39.3	100.4	190.6	12		155.7	40.0	
13				17.6	34.7		35			370.5	260.3
Assy						300.5	Assy				335.3
Short Rails: Total Distance = 953.9m							**Slates: Total Distance = 1614.9m**				

4.3. *Simulation*

Data collected from direct observation of the processes in the manufacture of bunk beds formed the input for the simulation runs using Arena through which flow bottlenecks were identified as well as those workstations that were starved, busy, high frequency of breakdowns and large queues sufficient to advise the company on the use of preventive maintenance. The output from the simulation model provided the quantitative results showing the average time spent by the bunk beds in the system, average hourly output and average times spent by the respective machines while starved, busy, blocked or broken down. Table 5 shows the qualitative results extracted from the Arena simulation outputs at the 10 workstations, which tallied with the direct observation and hence formed a sufficient basis to optimize the system by recommending additional machines to operate in parallel for the those that consistently had large queues.

Table 4. Parameters for the simulation model in the manufacture of bunk beds

Work Station	**Parameter**			
	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

5. Discussion and Recommendations

Based on the 3 techniques employed to identify bottlenecks, backtracking process paths and the grouping of workstations based on similar functions, 3 possible arrangements of workstations were considered. The machine distance matrix that was created showed the distance between interacting workstations in a symmetrical array format with zero diagonal. The *From To* matrix (Table 2) of parts movement was also a square symmetrical array but additionally shows the number of movements between interacting workstations and the *Total Distance* matrix (Table 3) is the product of corresponding workstation distances and number of movements. The resulting arrangements for the 3 possible options is summarized in Table 5.

Table 5. Evaluation of the 3 possible plant layout models

Overall	**Current layout**	**Model 1**	**Model 2**	**Model 3 (strategic)**
Total distance travelled (meters/month)	143497	80473	80461	74444
Approximate total monthly cost/$	24107.00	13520	13517	12506
Cost savings$/month	---------	10587	10590	11601
% Cost savings	---------	44	44	48

Although the cost savings for the 3 models were all in the same region, model 3 was selected as the most strategic, the resultant layout of which is shown in Fig. 3, with systematic flow of processes and grouping of workstations.

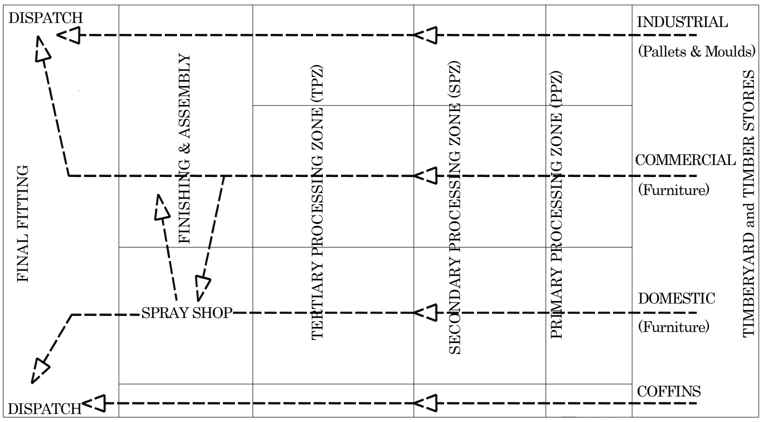

Fig. 3. Reorganized plant layout in functional groups

A contemporary approach in the analysis of the layout and materials handling at the inception of the research was carried out and the data collected enabled the reorganization of the plant to allow for smooth and continuous flow of materials with minimal backtracking. Utilization of space, particularly the movement of parts with minimal interference between workstations was one of the key drivers to ensure a safe operating environment. The 4 spray paint shops that were initially in each of the departments were grouped and strategically relocated close to the final assembling zone, leading to a reduction in congestion and improved quality of products as parts were now moved in one direction without the need for transporting them back to the dusty machine shop environment which would require further polishing before dispatch. Materials handling equipment such as forklifts and trolleys were reallocated appropriately depending on sizes of parts to be transported. Gangways were cleared as a result of grouping of workstations as well as disposing of old and idle equipment allowing for the free movement of forklifts, less interference and a safe working environment. In addition to recommending the disposal and replenishing of old and conventional equipment that frequently broke down, management was also urged to consider investing in automated materials handling equipment such as the installation of conveyors or automated guided vehicles. However the major challenge in this regard was the company’s lack of financial capacity which could be resolved gradually from the proceeds accrued from the savings in costs in the reorganized layout.

6. Conclusions

Reorganization of the plant layout for the furniture manufacturing company was accomplished through functional grouping to ensure workstations with similar functions are close to each other, analysis of the distances travelled by parts in order to reduce backtracking of process paths, reallocation of materials handling equipment for optimal use and simulation to identify bottlenecks in production as well as predict performance of the system. The selected model of the redesigned plant layout achieved 48% cost savings as a result of the reduction of transportation distances and idle times as well as increases in throughput. The use of simulation enhanced production planning and scheduling resulting in less overloading and queues at busy workstations as it enabled tracking and monitoring of the processes and timely delivery of quality products to customers. However, the company's major challenge was on old and conventional equipment that frequently broke down. Recommendations were made to replenish these as well as consider investing in automated transportation of parts by installing automated conveyors or automated guided vehicles.

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