A two-phase approach to modeling the operational flow in FMC's

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Flexible Manufacturing Cells (FMC's) are the unit building blocks of any form of programmable automation, which is best suitable to handle the make-to-order production mode. As a result, a proper modeling for a FMC is of utmost importance, since it involves high level of investment together with superb flexibility requirements. This paper presents a two-phase approach to model operations within FMC's. In the first phase a FMC is modeled as a Closed Queuing Network (CQN). The number of pallets is so large, that the bottleneck station has utilization of 100%. Following the determination of the bottleneck station the performance criteria of the other stations are derived. The result can be considered as the asymptotic behavior of the FMC for large number of pallets. Using these outcomes in the second phase, a process mapping simulation is performed using Optima! Micrografx® on the operational flow performance of the system. A set of simulation experiments has been conducted under different operational scenarios. Effects of AGV server availability, product complexity, job execution time variation, and station buffer size were investigated. The results of the second phase include detailed analysis of the system transactions including system resources utilization, cycle time constituents, and other useful system performance evaluators.

تعد خلايا التصنيع المرنة من وحدات البناء الرئيسية فى أية منظومة حديثة للأنتاج تعتمد مبدأ التصنيع حسب الطلب. لذا، فهناك العديد من المحاولات الجادة لدراسة هذا النوع من منظومات التصنيع من خلال بناء نماذج تحليلية ونماذج محاكاة وغيرها نظراً لأرتفاع تكاليف تشغيلها فضلاً عن الأستثمارات الأولية المرتفعة فى معداتها. يقدم هذا البحث طريقة ثنائية الأطوار لتمثيل إنسياب العمليات داخل منظومات التصنيع الخليوية. حيث يقترح الطور الأول دراسة المنظومة كشبكة طوابير مغلقة فيها عدد كبير من المنصات كما أن معدل إستغلال محطة الإختناق بها يبلغ ١٠٠% ويلى ذلك إعتماد الطرق التحليلة الكلاسكية لحساب مؤشرات الأداء لبقية المحطات فى المنظومة وهى الطريقة المعروفة بأسم طريقة التوزيع الأستاتيكى. إستخدمت النتائج التى أمكن الحصول عليها فى الطور الأول فى بناء طريقة التوزيع الأستاتيكى. إستخدمت النتائج التى أمكن الحصول عليها فى الطور الأول فى بناء نموذج محاكاة بإستخدام حزمة برامج (Optima Micrografix) إعتمادا على سريان وإنسياب العمليات داخل الخلية. وتم دراسة مجموعة من العوامل الرئيسية وتأثيرها على عدد من مؤشرات الأداء فى نموذج المحاكاة، منها: تأثير إتاحة خادم AVG – تأثير درجة تعقيد المنتج – تأثير التغير فى أزمنة الإنتاج – وتأثير التغير فى حجم مساحة التخزين الأحتياطية أمام كل محطة داخل الخلية فى كل التجارب السابقة تم تسجيل معدلات إستغلال موارد الخلية المختلفة – عناصر زمن الدورة الواحدة علاوة على غيرها من المؤشرات الهامة. لقد أسفر البحث فى نهايته عن مجموعة تفصيلية من التوصيات المفيدة فى تشغيل منظومات التصنيع الخيلوية تتعلق بعناصرها البنائية وسران العمليات وطيفية تعظيم الأستفادة من مواردها بهدف رفع قدراتها التنافسية.

Keywords: Process mapping simulation, Performance evaluation, Production system modeling,. Static allocation approach

1. Introduction

In a make-to-order environment, production operations are performed based on customer tailored end products, with jobs produced to order rather than for stock. Such mode of operation is becoming predominant in today's manufacturing due to the continuously changing customer choices and the ever-increasing demand for variety. Because of its high capability to handle the aforementioned characteristics, Flexible Manufacturing Cells (FMC's) are the unit building blocks of any form of programmable automation that is best suited to handle the make-to order mode. An FMC is characterized as a production system consisting of automatically reprogrammable stations, automated tool changers,

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automated material handling (transporters), and attendant shop floor control [1, 2]. An FMC operations primarily refer to repetitive and short term activities that require efficient, timely, and adaptive responses to jobs and part pallet flow within the cell Appropriate areas of interest include job execution, loading sequences, deadlocks, and response to resource disruptions such as unavailability of stations or transporters [2, 3]. Detailed understanding of operational information, beyond simplified approaches, is required for efficient production. As a result, a proper modeling for a FMC is of utmost importance, since it usually involve high level of investment together with superb flexibility requirements. On the contrary, inadequate operation model may lead to high cost and ineffective use of the manufacturing resources at all production levels. Due to the dynamic complex nature of FMC's and inherent differences between systems, researchers argue that generic, analytical optimal seeking approaches may be too difficult and/or too abstracted to present real-time situations [1, 4, 6]. Meanwhile, simulation-modeling approach has been applied successfully to solve much of long-term planning and design of manufacturing systems [7-10]. Some reported applications of simulation for operational model of flexible manufacturing cells include emulation of control systems, adaptive scheduling and planning, displays of system conditions, performance forecasting, as well as implementation into a shop floor controller [11- 13].

For instant, a modeling-based problem solving approach was developed for the design, analysis, and off-line programming of robotic workcells (a sort of FMC's) using an interactive and virtual environment in which credible solutions for workcell designs can be obtained. However, conducting workcell simulation studies via such simulation packages require designers to carry out complex processes of modeling, programming, and analysis, which often results in technical challenges and difficulties [14]. In another attempt, a simulation model was developed and tested using Taylor II to justify the implementation of a Flexible Manufacturing Cell (FMC). Simulation models are developed, tested, verified, and the model sensitivity is evaluated. The simulation models claim providing valuable information about performance parameters, critical elements, and bottlenecks that may appear when the line capacities have been altered [8]. Never the less a more in-depth understanding of system parameters and clear understanding of the improvements achieved by switching to FMC could be achieved if such models are combined with a preliminary deterministic system equations.

A recent work describes a novel method for detecting the bottleneck in a discrete event system by examining the average duration of a machine being active for all machines. The machine with the longest average uninterrupted active period is considered the bottleneck. The results are highly accurate, distinguishing between bottleneck machines and non-bottleneck machines with a high level of confidence. This approach is easy to use and can be implemented into existing simulation tools while requiring an analytical model of the cell log file [6].

Simulation models however and sometimes lacks introductory information about status in addition to analytical models that would describe the operational behavior of the manufacturing system under different conditions.

On the other hand, while there are numerous research articles conducted in areas related to the operation and performance enhancement of flexible production systems, few were devoted to combine analytical models to other modeling platforms like simulation-based domains [9, 13]. Combining the two approaches utilizes the benefits offered by having analytical performance measures with the stochastic nature of operation provided by simulation techniques. In spite of that, the use of simulation has appeared favorable to purely analytical methods, which often fail to capture complex interactions of a particular FMC [15].

In this pretense, the main objective of this work is to present, analyze and investigate the operation flow of a flexible-manufacturing cell (FMC) using a two-phase approach. The first phase includes adopting an analytical model used for deadlock prevention in FMC's and is well known as the statistic allocation approach [3]. Models for such technique were modified and coded in a Microsoft office Excel® to provide essential preliminary information for the operations of the FMC. Results of that model are used for the second phase analysis that is a set of process mapping simulation experiments conducted on the same FMC. Results of the second phase are detailed system performance indices under effects of variation of a set of operation flow parameters including; AGV availability, product complexity, pallet part execution time, and stations buffer size.

This paper is organized as follows: Section 2, follows this introduction and presents the FMC under investigation together with the modeling approach adopted all-over this work. Section 3 presents the static allocation model approach for dead lock prevention in FMC's. A case study with a hypothetical real life data is then introduced to verify and validate the analytical model. Results coincide well with reported output of similar applications. Section 4 outlines a methodology for representing the same FMC using process-mapping simulation, which is used by the simulation platform all over this work. The concept and procedure of simulation is demonstrated together with the architecture of the optima micrografix® software [16] utilized to conduct several simulation experiments in the same section. Section 5 offers comprehensive conclusions as well as future research directions in this area.

2. System characteristics

In this paper, a flexible-manufacturing cell (FMC) system configuration similar to the one shown in fig. 1 is considered. The basic elements of the illustrated FMC include a set of (m) work stations and its resources (tool magazine, tool storage, buffers, etc.), material handling devices (AGV, conveyors...), cell accessories (pallets, pallet pools, fixtures, etc.) and the cell control computer. Arrows within the cell indicates the operational flow from and to different system entities.

3. System modeling

3.1. Phase (1) - deadlocks prevention using static allocation approach

One of the major problems, which would arise during the operation of a FMC, is the evolution of deadlocks. It is a situation where each of a set of two or more jobs keeps waiting infinitely for the other jobs to release recourses. Deadlocks may arise as the final state of a complex sequence of operations on concurrent jobs passing through the system, and are generally difficult to predict, [2], and lead to degradable performance and ultimately zero throughput. Rather, deadlock prevention is used as a widely accepted strategy for the operation of FMC's. The static allocation procedure is used to eliminate completely the possibility of deadlocks, [17]. In this technique the resource allocation is made so as to break one or more of the necessary operating rules. The procedure is described in many articles, for example in [1] and [18]. However, it is compiled here with some modification to serve as an introductory phase of the proposed model. Thus, the system is modeled first as a closed queuing network (CQN). The number of pallets is large, that the bottleneck station has utilization of 100%. Following the determination of the bottleneck station the performance of the other stations are derived. The results can be considered as the asymptotic behavior of the FMC for large number of pallets and the last station (M) is considered to be the transportation station (central server).

The following notations and assumptions are used:

m = index of station, e= bottleneck station, b_i (m) = mean processing time of job (i) at station (m), p_i(m)= relative arrival frequency of job (i) at station (m) , $0 \leq pi \leq 1$, and S(m) = number of servers for station (m), X(m)= Throughput , U(m) = utilization, N= number of pallets.

There are always (N) pallets with work parts circulating in the cell. Unlimited buffer size for each station is available. Thus no starving or blocking is expected. A station may accommodate more than one server with FCFS queuing discipline used. All operation times are exponentially distributed with parts flow through the network by the arrival frequency.

With a large number of pallets, the bottleneck station (e), and its throughput are derived from:

$$e = \max_m \left(\frac{p_m \cdot b_m}{S_m}\right). \tag{1}$$

$$X_e^{\max} = \frac{S_e}{b_e} . \tag{2}$$

The throughputs and utilization of the non-bottleneck stations could be calculated using the following eqs. [13, 18]:

$$X_m(N) = P_m . X_M(N) \qquad m = 1,2,\ldots M, \qquad (3)$$

$$U_m(N) = \frac{b_m . X_m(N)}{S_m} \qquad m = 1,2,\ldots M. \qquad (4)$$

3.1.1. Phase (1): model inputs

Table 1 gives the input FMC data necessary to get the performance measures having a single server.

The same cell data will be tested under increasing the number of server and variable number of pallets circulating within the system. Cell performance is measured in terms of station Throughput (Xm), Station Utilization (Um), and Queue length, i.e. number of pallets waiting at station (Nm). The previous models have been programmed on an excel spreadsheet with a developed add-in. Results are shown in tables 2 to 5 and figs. 2 to 5.

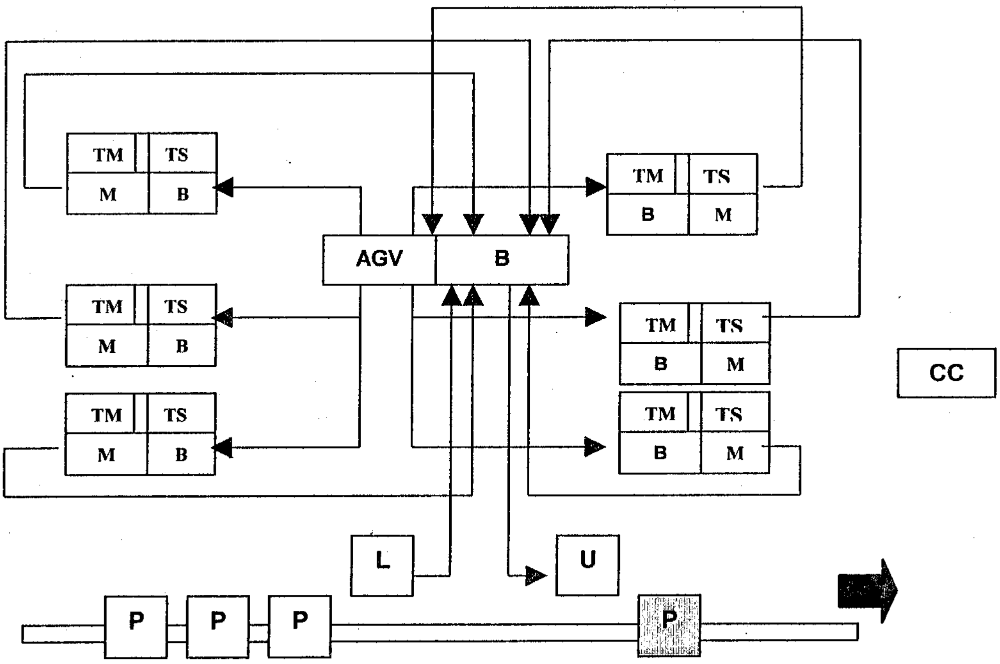


Fig. 1. FMC configuration P: Pallet- L: Load Station – U: Unload station- B: Buffer- M: Station- TM: Tool Magazine- TS: Tool Storage- CC- Cell Computer and program storage.

Table 1
Input data to phase (1) model: static allocation approach

Station number (m)	1	2	3	4	5	6	7
b(m), minutes	90	295.67	193.33	5.9	56	69	89
p(m)	0.1	0.1	0.08	0.02	0.3	0.4	1
S(m)	1	1	1	1	1	1	1

Table 2
Phase 1- model output: effect of number of servers on cell throughput (job min $^{-1}$)

Scenario	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
S(7) = 1	0.001124	0.001124	0.000899	0.000225	0.003371	0.004494	0.011236
S(7) = 2	0.002247	0.002247	0.001798	0.000449	0.006742	0.008989	0.022472
S(7) =3	0.003371	0.003371	0.002697	0.000674	0.010112	0.013483	0.033708
S(7) = 4	0.003382	0.003382	0.002706	0.000676	0.010146	0.013529	0.033822

S(7) = number of servers for station (7)

Table 3
Phase 1- model output: effect of number of servers on station utilization (%)

Scenario	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
S(7) = 1	10.11%	33.22%	17.38%	0.13%	18.88%	31.01%	100.00%
S(7) = 2	20.22%	66.44%	34.76%	0.27%	37.75%	62.02%	100.00%
S(7) =3	30.34%	99.66%	52.13%	0.40%	56.63%	93.03%	100.00%
S(7) = 4	30.44%	100.00%	52.31%	0.40%	56.82%	93.35%	100.00%

S(7) = number of servers for station (7)

Table 4
Phase 1- model output: effect of number of pallets on cell throughput (job min $^{-1}$)

Scenario	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
N=1	0.000533	0.000533	0.000427	0.000107	0.0016	0.002133	0.005332
N=2	0.000827	0.000827	0.000662	0.000165	0.002482	0.00331	0.008274
N=3	0.000983	0.000983	0.000786	0.000197	0.002949	0.003932	0.00983
N=4	0.001061	0.001061	0.000848	0.000212	0.003182	0.004242	0.010605
N=5	0.001097	0.001097	0.000877	0.000219	0.00329	0.004387	0.010967
N=6	0.001113	0.001113	0.00089	0.000223	0.003338	0.004451	0.011126
N=7	0.001119	0.001119	0.000895	0.000224	0.003358	0.004477	0.011193
N=8	0.001122	0.001122	0.000898	0.000224	0.003366	0.004488	0.011219
N=9	0.001123	0.001123	0.000898	0.000225	0.003369	0.004492	0.01123
N=10	0.001123	0.001123	0.000899	0.000225	0.00337	0.004493	0.011234

N = number of pallets circulating within the cell

Table 5
Phase 1- Model output: effect of number of pallets on queue length

Scenario	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
N=1	0.048	0.158	0.082	0.001	0.09	0.147	0.475
N=2	0.078	0.283	0.139	0.001	0.151	0.262	1.086
N=3	0.095	0.373	0.173	0.001	0.19	0.342	1.825
N=4	0.105	0.431	0.192	0.001	0.212	0.393	2.666
N=5	0.109	0.464	0.202	0.001	0.223	0.422	3.579
N=6	0.111	0.482	0.207	0.001	0.229	0.437	4.534
N=7	0.112	0.49	0.209	0.001	0.231	0.444	5.513
N=8	0.112	0.494	0.21	0.001	0.232	0.447	6.503
N=9	0.112	0.496	0.21	0.001	0.232	0.449	7.499
N=10	0.112	0.497	0.21	0.001	0.233	0.449	8.497

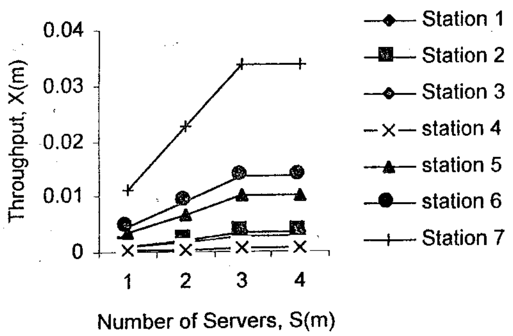


Fig. 2. Throughput vs. number of servers.

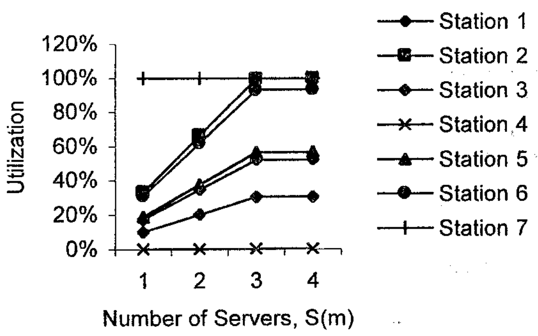


Fig. 3. Utilization vs. number of servers.

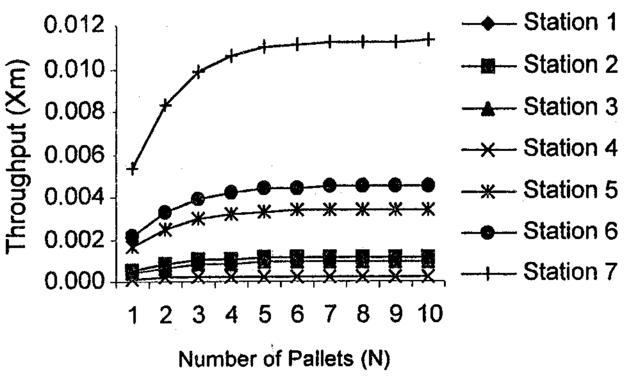


Fig. 4. Throughput vs. number of pallets.

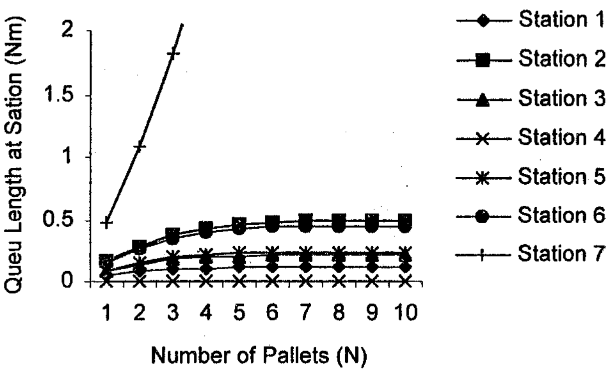


Fig. 5. Queue length vs. number of pallets.

3.1.2. Phase (1): model outputs

Tables 2 to 5 together with figs. 2 to 5 illustrate phase (1) model outputs. The analysis yields that station (7), i.e. the AGV, is the bottleneck station. Table 2 and fig. 2 show that as the number of servers increases, station throughput increases. The bottleneck station maintains the largest throughput among all stations. Increasing the number of servers above certain level (m=3 in this case) has no further improvement on throughput of all stations. Similar behavior was noticed for the FMC utilization, as shown in fig. 3. The bottleneck station possesses the highest utilization (100%). Other stations have lower utilization values which ranges between (45%) for station (2) to as low as (8%) for station (4). Such variability is mainly attributed to consequences of the assumptions made by the approach used as reported in [15]. However, as the number of servers increases, a noticeable improvement in other stations utilization occurs. Again, a limiting value is posed, particularly when m=3 in this case, above which no improvement will happen. Table (4) and fig. 4, both exhibit the effect of changing the number of pallet circulating within the cell system on throughput performance. Increasing the number of pallets is practically an indication for the productivity of the cell and the degree of flexibility. Thus, the effect of increasing the number of pallets has a dramatic impact on throughput of the bottleneck station. While it reflects little impacts on rest of the stations. Such a trend is limited to a certain number of pallets, N= 4 in this case, after which no further improvement in throughput is noticeable. On the contrary an asymptotic behavior is perceived. Similar behavior is obtained for the effect of increasing number of pallets on queue length in front of each station.

As the number of pallets increases, the queue length of station (7), bottleneck sharply increases. While the impact of increasing the number of pallets is less on rest of the cell stations. Those results are shown in table 5 and fig. 5.

The previous model assumes an infinite local buffer size for each resource to overcome the problem of deadlocks. That is, jobs will never be blocked at any station. Also, resources are considered always available to serve jobs. Except stations other system resources are not examined in the analysis. More realistic formulation of the problem would consider a limited buffer size in front of each resource type, together with putting AGV availability and station interruptions into consideration. Further, results of the analysis should include more detailed information about system resources, cycle time and queue elements.

In addition to the above realistic conditions, studying the stochastic nature of the operational flow within the cell would be considered an asset since it brings many of the factors which have been abstracted in the previous model, for simplification, into one domain. The following section is a simulation study for the FMC using process-mapping approach.

3.2. Phase (2): process mapping simulation

A process map with a discrete-event simulation test bed is used here to model operation flow within a FMC. Drawn as symbols a process map consists of a set of activities linked together and having certain sequence and attributes. Attributes of each activity describe its duration, distribution, input characteristics, and resources used. It also includes task behavior, queues, and output configuration. Activities occur in a series of individual steps, which are invoked by the movement of transactions. A transaction in this model is set to be an operation of the FMC entities.

3.2.1. Simulation parameters and model input

Fig. 6 describes the operation flow sequence for a FMC cycle as a process map. Four subsequent stages distinguish that operation flow cycle, namely; Setup and part arrival, Pallet loading, execution, and finally unload and finish cycle. Specifically, Parts on pallets are assumed to arrive with a Poisson distribution (mean=5 minutes) in batches between 1-15 parts uniformly distributed. Number of dedicated pallets circulating within the cell is assumed to be constant (N=4). Pallets wait for availability of AGV in a pallet pool of size = 3 to be selected for transfer to stations. Availability of AGV is prefixed to be 95% in the reference model. Queue method is assumed to have a FIFO dispatching pattern. Pallets are moved to station (m) of constant buffer size = 2 pallets, where it waits for availability of next station. It is assumed that in 90% of the cases a station is available. Workers then check for existence of part programs loading in the cell PC, where programs are loaded with time uniformly distributed between (5-10 minutes). Workers also checks for availability of necessary tools, and they fetch tools and load it into tool magazine. Load time is uniformly distributed between (3-12 minutes.). Parts are then executed with processing time of mean = 50 minutes. Parts are unloaded and wait for availability of AGV in station buffer. In 50% of the transactions parts on pallets are transferred to another station and the cycle is repeated. Rest of the parts are unloaded and moved back to pallet pool.

3.2.2. Process simulation procedure

Fig. 7 shows a conceptual view of the simulation procedure as performed by the *Optima! Micrografx®* version 2.5 package which is the modeling and simulation environment used through out this paper [16]. A description of the sequential steps to simulate a process in that procedure is summarized as follows:

a) Create process- activity maps: A process is created which is composed of departments. Each department is a horizontal area in a process map that contains symbols and connections. The symbols represent activities that occur within the individual department.

b) Add duration for review: Duration for each activity is added, where the duration is the amount of time required for an activity to complete processing.

c) Set activity resource usage : A resource is a worker, station, AGV, pallet or other asset used to process a transaction. More specifically, in an *Optima! Micrografx®* Process map, a resource provides the mechanism used by an activity to process transactions. When there are multiple transactions being processed, they can contend for resources.

An important distinction to make is that resource usage, which is specific to an activity, is different from resource allocation, which is the total number of resources available to a department.

The following characteristics can be defined for a resource:

- *Choosing a resource;* choose from the list of available resources.
- *Resource assignment type;* specify whether the activity uses, acquires, or releases a resource, *Resource behavior;* specify how the model acts if the resource is unavailable, *Resource quantity;* set the number of resources required by the activity, *Resource schedule;* define the active times during which the activity can use the resource, *Resources waiting:* This describes what happens if the resource has to wait, for example, for a transaction or other resources to become available.

d) Define the simulation data: Simulation data are defined using the following sub-system procedure:

- *Edit the run setup;* the run setup specifies information about, among other things, the amount of time that is covered,
- *Set simulation period,*
- *Edit the generator;* the generator introduces transactions at a specified rate into the Start symbol,
- *Set the resource allocation.*

The resource allocation is the total number of resources available to the different departments in the process map. Each department has a number of workers, energy capacity, raw materials, and so forth. These are used to move one transaction through the department at a time.

e) Run a trace simulation: At this point, the model is ready to simulate. The simulation can run in the background or in the trace window. The trace window uses color and animation to display the different states of transactions being processed during simulation. The trace simulation takes approximately 6 minutes. A status line for information about the simulation completion is displayed. When the trace is finished, a report window is displayed with data about the simulation.

f) Analyze the report results: After the trace simulation is finished, a report is generated which includes the data that is produced as a result of the simulation.

3.2.3. Simulation setup data

Fig. 8 shows a set of screen shots of simulation setup and data preparation procedure used in this phase. Simulation time is assumed to last 5 calendar days with a standard schedule (8am-12pm/Monday to Friday). Transactions are introduced into the start activity at a special rate using a generator. The generator type is presumed to be inter-arrival with a rate exponentially distributed of mean = 2 minutes. Active period to generate transactions is set to be between the start and end of simulation and waiting time is blocked. Simulation experiments assumes a reference resource level of AGV=1, Buffer size for all stations=1, Number of pallets = 4, number of workers = 4 for each cycle section, Tool Storage/Station (TS) = 1, Tool Magazine/station (TM) =1. Cost attributes attached to resources are also introduced based on international standards and market prices

3.2.4. Simulation experiments

A set of simulation experiments has been conducted to investigate the effect of different operating conditions that would face the model FMC in a definite environment. For each experiment different system performance evaluators are derived.

a) Effect of AGV server availability. Where availability at time *(t)* is the probability that the system is operational at that time *(t)*. Availability of the cell AGV was tested for a range between 100% down to 60%, with a step of 5%.

b) Effect of Product complexity. Where complexity indicates that the product requires multiple operations. This is interpreted, as the probability that number of jobs and consequently stations needed to manufacture the product tends to be larger. Product complexity has been classified, using that concept, into three categories: products with very high degree of complexity (probability of more than one station is needed for fabricating the product is 90% and above). Medium degree of complexity (same probability is 80% and lower) and finally, low degree of complexity (same probability is 50% and lower).

c) Effect of job (part pallet) execution time variation. In the base model job execution time has been assumed to have an average value of 50 minutes. Variation in job execution time is assumed to take place with a uniform distribution starting with a level between 10 to 20 minutes and then increased by a step of 10 minutes up to a range between 10 and 70 minutes. In practice, this situation may portray the flexibility of the Cell. The wider the range the more flexible is the system.

d) Effect of station buffer size. Buffer size, (N)

e) in front of cell stations has been experimented for a range between N = 1 (base model) and N = 12.

3.2.5. Phase (2): model output(s)

a) Effect of AGV availability on FMC performance: Table 6 with figs. 9 and 10 illustrate results of simulation runs at different AGV availability values. In table 6 and fig. 9, FMC performance is measured by average job (part pallet) cycle time, Average work time, Average block time and Average wait time. The large portion of job cycle time mainly comes from its waiting time portion. As AGV availability decreases from (100%) to (90%) cycle time decreases from (27.64) hours to (20.41) hours mainly due to the decrease in cell waiting time (24.81) hours to (17.63) hours. The average work and blocking time portion are tiny in the cycle time and no significant change occurs in behavior due to change of AGV availability. As AGV availability decreases to 80% Cycle time decreases down to (6.71) hours, again, due to the sharp decline in the cell average wait time to (4.68) hours. If AGV availability decreases to levels beyond 80%, cycle time rises, in turn, due to the increase in average waiting time. However, if AGV availability values drop below

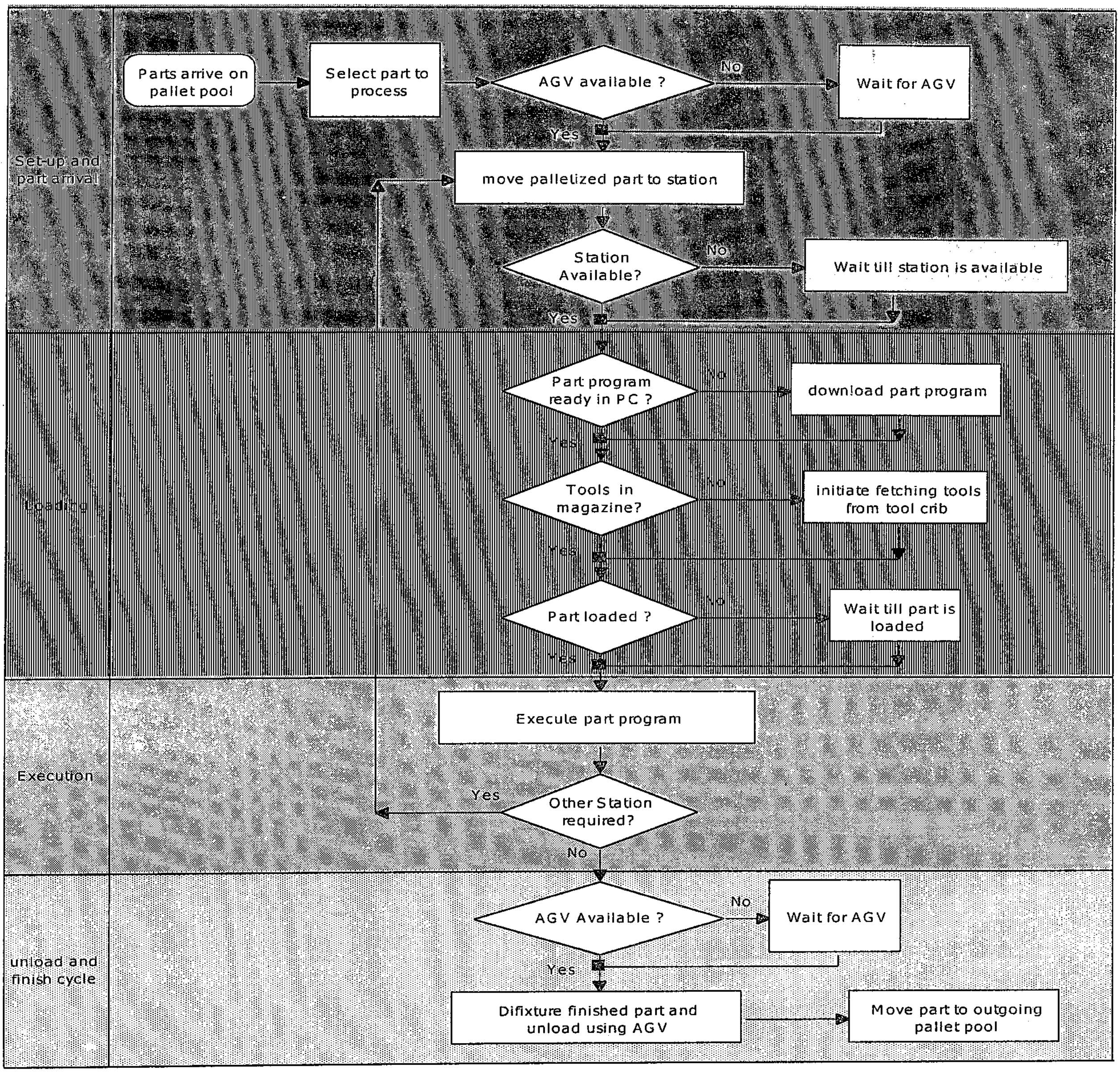


Fig. 6. Process map of the operational flow within FMC , Optima! Micrografx V.2.5.

70%, no significant effect is noticeable on any of the cell performance indices Such a behavior is mainly attributed to job queues that wait before the stations in case AGV availability is high, (i.e. > 80%). While job queues that wait before the AGV tends to increase, in case AGV availability is getting lower, (i.e. < 80%). The previous queue analysis is shown in table 6 and fig. 10. Resources utilization are given in table 6, where cell stations always show high utilization > 90%. However, AGV and pallets utilization varies greatly as AGV availability changes. AGV utilization increases from as low as (33.8%) to (64.9%) at AGV availability of (80%), which represents the best value attained. AGV utilization drops again to (36.6%) for AGV availability values < 70%. A similar characteristic is noticed for pallet utilization while rest of resources shows a reverse attitude combined with low utilization values. From the above analysis one may conclude that a quasi-optimal AGV availability should be close to 80%. Since performance indices (Average cycle time, Average wait time, and resources Queue length) are minimum and resources utilization is maximum.

b) Effect of product complexity on FMC performance: As product complexity decreases from (90%) to (70%) average job cycle time slightly declined from (11.56) hours to (10.02) hours as shown in table 7 and fig. 11. This attitude is mainly attributed to the decline in average job wait time due to the increase of the AGV utilization from as low as 20.59% for (90%) complexity to 55.43% for (70%) complexity factor, as illustrated by table 7 and fig. 12. When part complexity factor tends to abridge below (70%), i.e. parts tends to be more simple, very slight effect is noticed on job average cycle time parameters (avg work, avg block, avg wait) and utilization of other resources (stations, pallet pool, buffer, etc.).

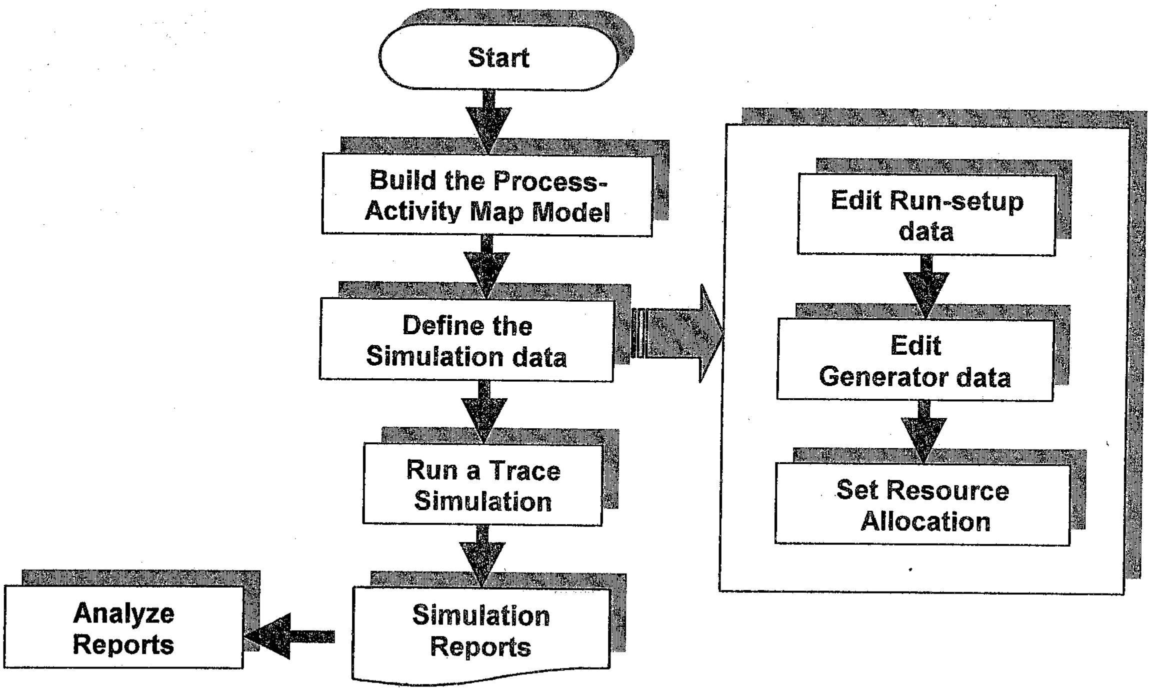
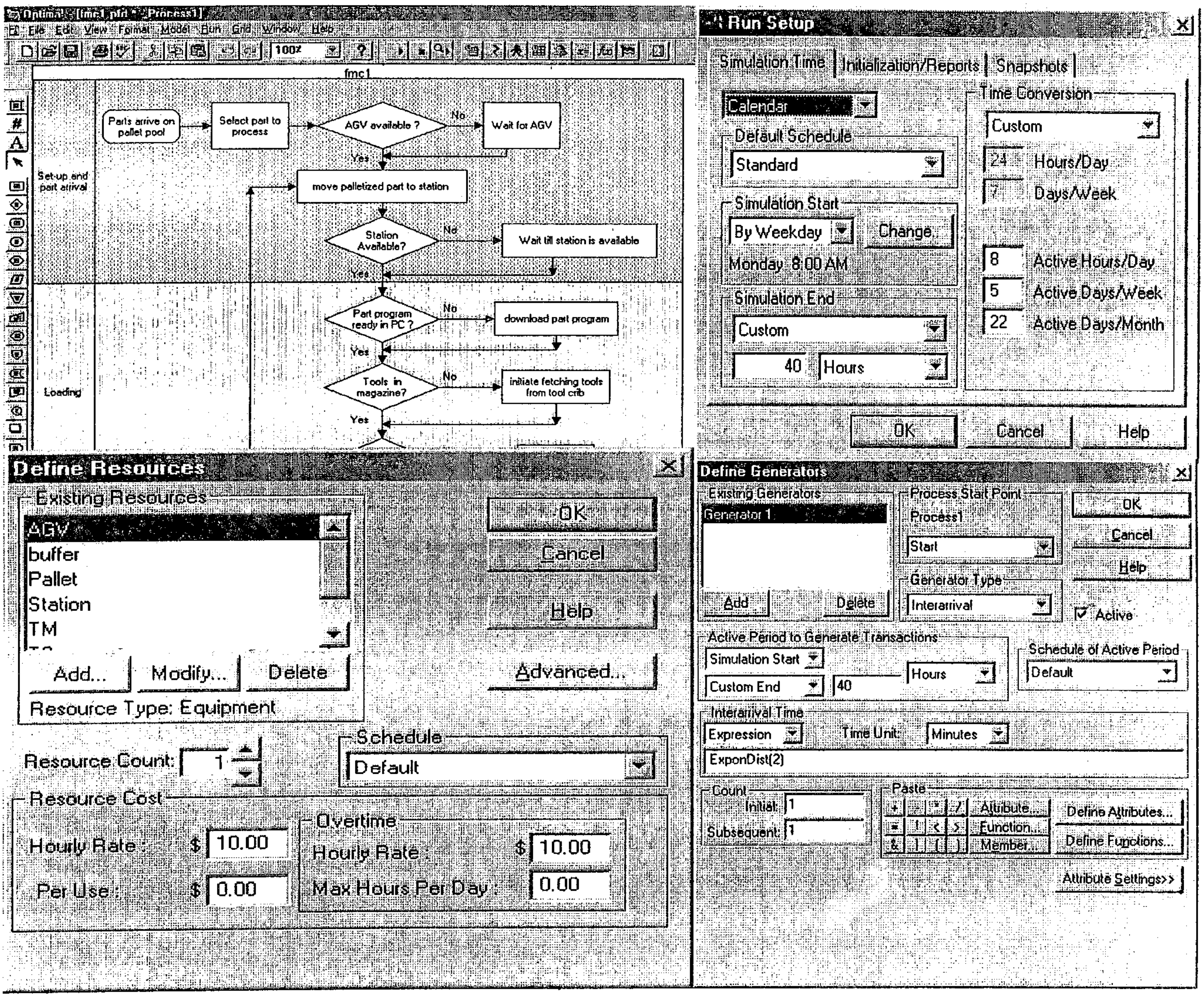


Fig. 7. Process mapping simulation procedure (Optimal Micrografx® V.2.5).

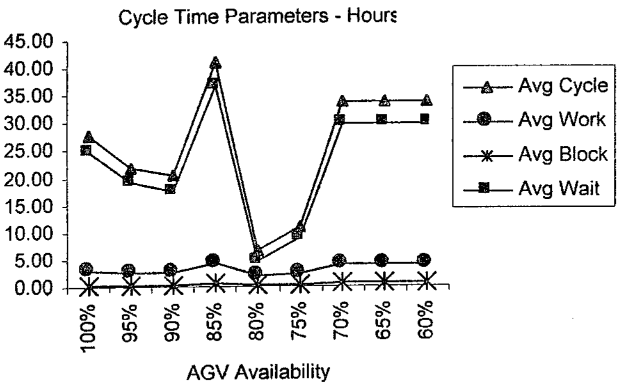


Run Setup – Simulation Time:
Calendar
Default Schedule: Standard
Simulation Start: By Weekday; Monday, 8:00 AM
Simulation End: Custom; 40 Hours
Time Conversion: Custom
24 Hours/Day
7 Days/Week
8 Active Hours/Day
5 Active Days/Week
22 Active Days/Month

Define Resources:
Existing Resources: AGV, buffer, Pallet, Station, TM
Resource Type: Equipment
Resource Count: 1
Schedule: Default
Resource Cost: Hourly Rate: $ 10.00; Per Use: $ 0.00
Overtime: Hourly Rate: $ 10.00; Max Hours Per Day: 0.00

Define Generators:
Existing Generators: Generator 1
Process Start Point: Process1; Start
Generator Type: Interarrival
☑ Active
Active Period to Generate Transactions: Simulation Start; Custom End 40 Hours
Schedule of Active Period: Default
Interarrival Time: Expression; Time Unit: Minutes
ExponDist(2)
Count: Initial: 1; Subsequent: 1

Fig. 8. Screen shots of the process simulation platform (Optimal Micrografx® V.2.5).



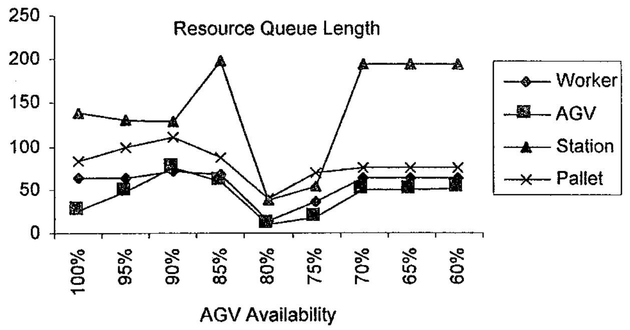


Fig. 9. Effect of AGV availability on cycle time parameters (hours).

Fig. 10. Effect of AGV availability on resource queue length (pallet).

c) Effect of job (pallet) execution time variation: As shown in table 8, figs. 13 and 14, when job execution time distribution varies to a range between (10-60) minutes, the cell average cycle time increases to 20.92 hours, as compared to 12.78 hours for a distribution range of (10-20) minutes. Again this increase is attributed to the growth in the cell average wait time, which increases from 11.02 hours to 18.11 hours for the same distribution variation. In accordance with those results, resource queue lengths fluctuate for all resources. As an example, it drops from 81 part pallets to 43 part pallets for stations under a job execution distribution variation from (10-20) minutes to (10-70) minutes. Lower resource utilization was noticed for all resources, except for stations. A slight improvement for the later resource was observed under the same job execution time variation, form 92.18% to 94.05%.

d) Effect of station buffer size : Results of this experiment indicates that the average cycle time tends to double with the increase of station buffer size due to the increase in the average wait time. This situation is displayed in table 10 and figs. 15,16. Average cycle time reaches (28.86) hours for a buffer size =12 as compared to (15.5) hours for a buffer size =1. However, resource queue length tends to Decline for almost all resources. For instance, queue length was 37 part pallet when buffer size = 1, and it declined to 22 part pallet when buffer size = 12. On the contrary, station resources utilization gradually declined during the experiment, while similar attitude with some how lesser degree was noticed for other resources. Fig. 16 displays that performance, where station utilization drops to as low as 45.48% as compared to 93.32% under the experiment range (buffer size between 1 and 12).

Table 6
Effect of AGV server availability on cell performance indices

	Cycle time statistics (hours)				Resource queue length (part pallet)					Resource utilization (%)				
AGV availability	Avg cycle	Avg work	Avg block	Avg wait	Worker	AGV	Station	Pallet	Buffer	Worker	AGV	Station	Pallet	Buffer
agv100%	27.64	2.83	0.34	24.81	64	25	139	83	0	33.2	33.8	96.6	52.3	10.9
agv95%	21.88	2.62	0.33	19.26	63	47	130	99	0	33.1	49.4	94.2	67.4	14.5
agv90%	20.41	2.77	0.37	17.63	72	75	128	111	2	35.0	67.2	94.3	89.4	17.7
agv85%	40.98	4.21	0.61	36.76	68	60	199	88	2	32.7	38.4	95.8	47.0	10.0
agv80%	6.71	2.03	0.30	4.68	14	9	38	39	0	17.7	64.9	93.8	82.6	9.6
agv75%	11.07	2.25	0.39	8.81	36	17	54	70	0	26.3	49.3	86.9	74.4	18.2
agv70%	33.82	4.03	0.65	29.79	63	50	195	76	5	33.6	36.6	96.3	44.5	12.1
agv65%	33.82	4.03	0.66	29.79	63	50	195	76	5	33.7	36.6	96.3	44.5	12.1
agv60%	33.82	4.03	0.68	29.79	63	51	195	76	5	33.8	36.6	96.3	44.5	12.6

Table 7
Effect of product complexity on cell performance indices

	Cycle time statistics (hours)				Resource queue length (part pallet)					Resource utilization (%)				
Product complexity	Avg cycle	Avg work	Avg block	Avg wait	Worker	AGV	Station	Pallet	Buffer	Worker	AGV	Station	Pallet	Buffer
90%	11.56	2.14	0.33	9.42	21	1	54	3	9	39.12	20.59	94.57	16.99	27.7
80%	11.22	1.76	0.19	9.46	19	16	53	3	11	37.66	46.86	94.57	21.93	29.06
70%	10.02	1.56	0.23	8.23	18	17	37	2	9	37.98	56.43	93.32	23.48	27.13
60%	13.46	1.87	0.21	11.59	19	19	39	2	9	38.9	56.45	93.32	24.77	29.48
50%	12.96	1.86	0.22	11.11	20	18	39	4	12	39.36	57.35	93.32	25.7	30.78
40%	11.94	1.77	0.19	10.17	18	18	35	3	10	38.98	57.2	93.11	24.61	30.83
30%	11.31	1.78	0.19	10.53	20	18	34	4	10	39.55	58.78	91.76	25.85	33.13

Table 8
Effect of pallet part execution time variation on cell performance indices

	Cycle time statistics (hours)				Resource queue length (part pallet)					Resource utilization (%)				
Variation (minutes)	Avg cycle	Avg work	Avg block	Avg wait	Worker	AGV	Station	Pallet	Buffer	Worker	AGV	Station	Pallet	Buffer
Base	2.97	1.75	0.25	1.22	3	17	12	0	7	15.55	14.19	23.65	17.05	27.29
10-20	12.78	1.76	0.38	11.02	43	19	81	3	12	43.36	52.87	92.18	24.48	32.71
10-30	11.13	1.92	0.37	9.21	17	7	36	0	9	32.63	32.28	68.68	17.34	26.04
10-40	15.56	1.77	0.36	13.78	27	9	60	2	11	40.2	41.26	94.05	19.44	27.29
10-50	19.86	1.76	0.25	18.11	28	20	61	4	7	38.73	56.24	93.84	22.67	25.1
10-60	20.92	2.16	0.33	18.77	18	3	53	1	7	38.01	28.78	94.05	16.63	23.13
10-70	14.03	1.75	0.22	12.28	17	6	43	2	6	35.14	26.25	94.05	13.36	18.13
10-89	14.4	2.31	0.29	12.09	28	14	53	4	5	37.5	46.73	94.05	20.58	23.85
10-90	13.61	1.71	0.21	11.9	21	7	52	0	7	37.68	26.89	94.26	16.69	25.1
10-100	14.12	1.89	0.23	12.23	20	6	45	0	7	36.28	26.99	94.05	15.58	22.4

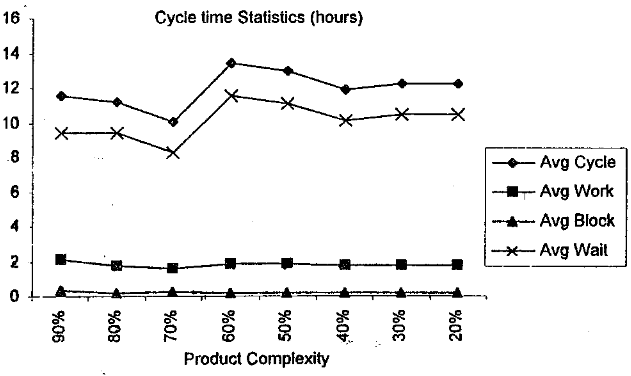


Fig. 11. Effect of product complexity on cycle time parameters (hours).

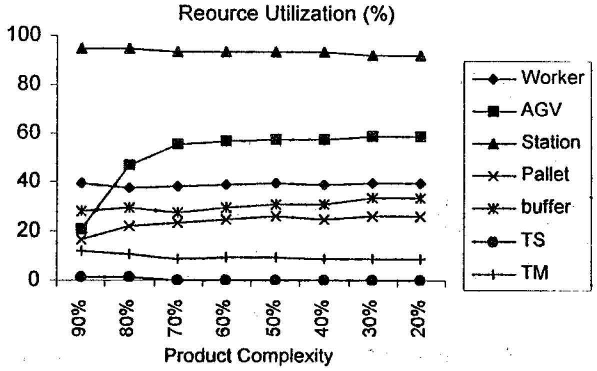


Fig. 12. Effect of product complexity on resource utilization (%).

Table 9
Effect of station buffer size on cell performance indices

	Cycle time statistics (hours)				Resource queue length (part pallet)					Resource utilization (%)				
Buffer size	Avg cycle	Avg work	Avg block	Avg wait	Worker	AGV	Station	Pallet	Buffer	Worker	AGV	Station	Pallet	Buffer
N = 1	15.5	1.98	0.23	13.52	18	17	37	2	9	37.98	55.43	93.32	23.48	27.13
N = 2	27.09	3.25	1.1	23.84	18	3	54	3	12	38.66	20.09	95.24	14.74	24.06
N = 4	8.49	1.94	1.28	6.56	15	4	39	0	13	35.36	21.68	89	17.91	23.13
N = 6	15.54	1.98	1.49	13.55	24	15	43	6	18	37.51	33.12	89.09	23.87	27.19
N = 8	12.93	1.7	1.64	11.22	23	10	44	12	15	33.74	33.94	79.93	24.66	23.13
N = 10	21.32	1.74	3.64	19.58	14	1	26	16	9	26.01	12.92	66.32	16.67	14.58
N = 12	28.86	1.71	6.39	27.15	14	0	22	20	12	20.49	10.95	45.48	18.71	17.6

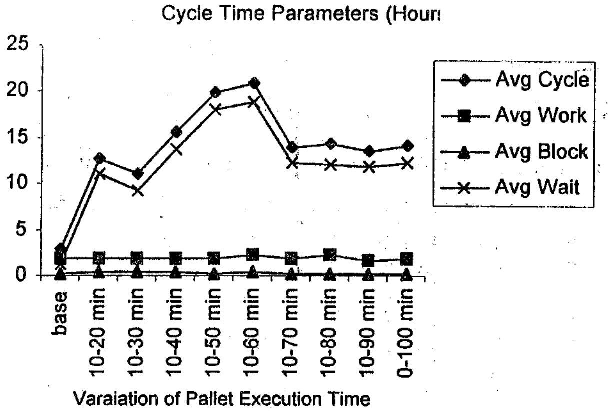


Fig. 13. Effect of f pallet execution time variation on cycle time parameters (hours).

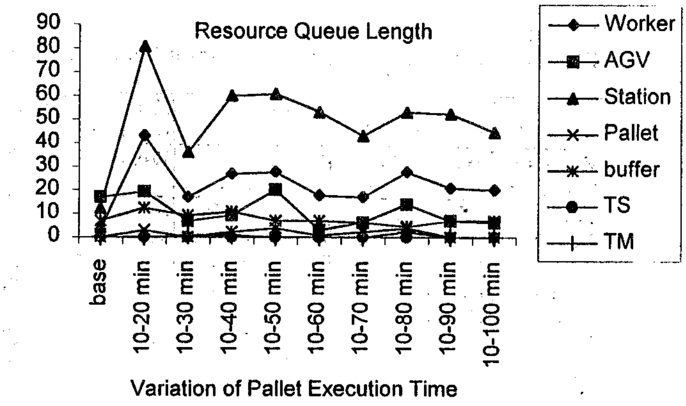


Fig. 14. Effect of pallet execution time variation on resource queue length (pallet).

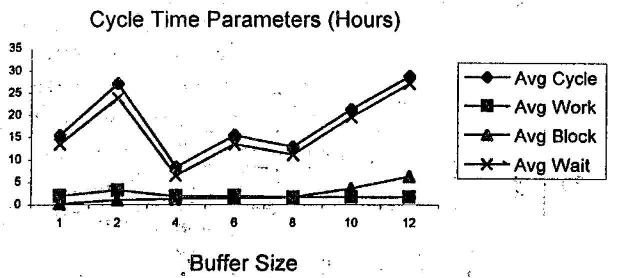


Fig. 15. Effect of station vuffer size on cell cycle time parameters (hours).

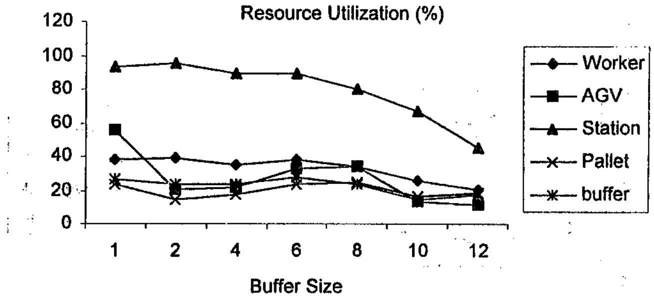


Fig. 16. Effect of station buffer size e on cell cycle resource utilization (%).

5. Conclusions

1. This paper combines analytical models (static allocation approach) to simulation-based platform (process mapping simulation) for modeling operation flow in FMC's. Linking the two approaches utilizes the benefits offered by having analytical performance measures with the stochastic nature of operation provided by simulation techniques. However,
2. The use of simulation has appeared favorable to the purely analytical method, which often fail to capture complex interactions of a particular FMC.
3. An FMC, which encompasses a set of standard workstations equipped with buffer, tool storage and tool magazine, is considered the subject system of the analysis. An AGV server plays the basic pallet transformer of the cell with the necessary load and unloads areas and other utilities. For that, the static allocation procedure is used to eliminate the possibility of deadlocks in the operation of the FMC. The technique also offers useful insights into the system, for instant the effects of some operation and design parameters (number of servers, number of pallets, etc.)
4. Despite its effectiveness, static allocation approach is implemented for long-run performance and almost it does not provide any information on the natural stochastic variability in the system. Therefore the technique is used here as a first-cut approximation to get an idea of where things stand and to provide guidance about what kind of simulation procedures might be appropriate in the next phase. Thus, Outputs of that first phase (analytical model) are meshed into the second phase model (simulation).
5. The first phase model outputs yields that the AGV Server, is the bottleneck station and as the number of servers increases, station throughput increases. The bottleneck station maintains the largest throughput among all

throughput increases. The bottleneck station maintains the largest throughput among all stations. Increasing the number of servers above certain level (m=3 in this case) has no further improvement on throughput of all stations.

6. Similar behavior is noticed for the FMC utilization, The bottleneck station possesses the highest utilization (100%). Other stations have lower utilization values which ranges between (45%) to as low as (8%). However, as the number of servers increases, a noticeable improvement in other stations utilization occurs. Again, a limiting value is posed, particularly when m=3 in this case, above which no improvement will happen.

7. Increasing the number of pallets is practically an indication for the productivity of the cell and the degree of flexibility. The effect of increasing the number of pallets has a dramatic impact on throughput of the bottleneck station. While it reflects little impacts on rest of the stations. Such a trend is limited to a certain number of pallets, N= 4 in this case, after which no further improvement in throughput is noticeable which indicates an asymptotic behavior

8. Similar reception is perceived for the effect of increasing number of pallets on queue length in front of each station. As the number of pallets increases, the queue length of the bottleneck sharply increases. While the impact of increasing the number of pallets is less on rest of the cell stations.

9. The second phase model considers more realistic formulation of the problem, in which a limited buffer size in front of each resource type is assumed, together with putting AGV availability and station interruptions into consideration. Further, results of the analysis include more detailed information about system resources, cycle time and queue elements. Through studying the stochastic nature of the operational flow within the cell, process-mapping simulation also brings many of the factors, which have been abstracted, in the previous model, for simplification.

10. FMC performance is measured in simulation by recording the average job (part pallet) cycle time, Average work time, Average block time and Average wait time. Other performance output indices include; queue length measured in number of pallets that wait for one of the cell resources and the cell resource utilization (%).

11. A set of simulation experiments has been conducted to investigate the effect of different operating conditions that would face the model FMC in a definite environment. For each experiment different system performance indices are derived. Thus, the experiments encompass the following: Effect of AGV server availability, Effect of Product complexity, Effect of job (part pallet) execution time variation and Effect of station buffer size. Other important operating conditions (factors) would have been considered in the analysis but they have been overlooked, on purpose, in the present investigation either due to the priority of the factors already considered or by reason of limitation of space or both.

12. As AGV availability decreases cycle time decreases. This phenomenon is mainly attributed to the decrease in cell waiting time. The average work and blocking time portion are tiny in the cycle time and no significant change occurs in behavior due to change of AGV availability. As AGV availability decreases to 80% Cycle time decreases down to (6.71) hours. If AGV availability decreases to levels beyond 80%, cycle time rises, in turn, due to the increase in average waiting time. However, if AGV availability values drop below 70%, no significant effect is noticeable on any of the cell performance indices. Such a behavior is mainly attributed to job queues that wait before the stations in case AGV availability is high, (i.e. > 80%). While job queues that wait before the AGV tends to increase, in case AGV availability is getting lower, (i.e. < 80%). Utilization of cell stations always show high utilization > 90%. However, AGV and pallets utilization varies greatly as AGV availability changes. AGV utilization drops again for AGV availability values < 70%. From the analysis one may conclude that a quasi-optimal AGV availability should be close to 80%. Since performance indices (Average cycle time, Average wait time, and resources Queue length) are minimum and resources utilization is maximum.

13. When studying the Effect of Product complexity on FMC performance, the experiment shows that as product complexity

decreases, average job cycle time slightly declined. This attitude is mainly attributed to the decline in average job wait time due to the increase of the AGV utilization. When part complexity factor tends to abridge below (70%), i.e. parts tends to be more simple, very slight effect is noticed on job average cycle time parameters and on resource utilization.

14. Simulating the effect of job execution time distribution variation indicates an increase in the cell average cycle time with the increase of such parameter. This increase is attributed to the growth in the cell average wait time. In accordance with those results, resource queue lengths fluctuate for all resources. It drops sharply for stations under a job execution distribution variation from (10-20) minutes to (10-70) minutes. Lower resource utilization was noticed for all resources, except for stations. A slight improvement for the later resource was observed under the same job execution time variation.

15. The average cycle time tends to double with the increase of station buffer size due to the increase in the average wait time. However, resource queue length tends to decline for almost all resources. On the contrary, station resources utilization gradually declined during the experiment, while similar attitude with some how lesser degree was noticed for other resources.

16. The simulation experiments presented in this work in addition to the methodology adopted could be expanded to include other operational flow parameters. Further, a similar approach may be used to analyze the effectiveness of material flow and/or the FMC production planning procedures, For instant, job scheduling and assignment problems.

17. The software used is highly flexible. Thus, it carries a high potential for interfacing of other models built by the author, using a popular platform (Microsoft excel® add-ins). A study of MRPII environment applied to the same FMC characteristics could be intensely encouraging.

18. Due to its significance, and ease of physical interpretation, process-mapping simulation is becoming the most widely used and accepted simulation methodology. For example, Arena® of Rockwell Software Inc., one of the most popular and flexible simulation platforms, is adopting the same methodology in its recent versions (Arena ®version 5.02) to build models. Such a change in modeling approach has dramatically improve and facilitate the use of this package. Consequently, the author is seriously considering the switch to that environment in similar future project analysis.

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Appendix

List of abbreviations and simulation syntax

syntax	interpretation
Elapsed time	Simulation run time
Avg cycle	Average cycle time for A Transaction to complete
Avg serv	Average service time
Avg work	Average working time
Avg res wait	Average waiting for resource time
Avg block	Average blocked time
Avg inact	Average inactive time when A resource is out of schedule
Avg wait	Average waiting time for A transaction to be processed
Tot cycle	Total cycle time
Avg busy	Average busy time that A resource spends working
Avg oos	Average out of service time
res utili%	resource utilization

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