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Defining production and financial data streams required for a factory digital twin to optimise the deployment of labour

C. Taylor[1], A. Murphy[1,+], J. Butterfield[1], Y. Jan[1],

P. Higgins[2], R. Collins[2], C. Higgins[2]

[1] School of Mechanical and Aerospace Engineering, Queen's University Belfast, Ashby Building, Belfast. Northern Ireland, U.K. BT9 5AH
[2] N.I. Technology Centre, Queen's University Belfast, Belfast, BT9 5HN
[+] Corresponding author: Tel.: +4428 9097 4095; E-mail: `a.murphy@qub.ac.uk`

Abstract. With the emergence of capable and low cost sensing hardware simulations may be driven from real time production data. Such simulation could be used to predict future system performance. However for effective decision making knowledge of system level behaviour beyond production e.g. financial metrics would also be required. The generation of standard accounting data from simulation models has received little attention in the literature. Herein a modelling approach is demonstrated to generate production and accounting data streams from a Discrete Event Simulation for an idealised production business. The paper demonstrates an approach to assess the influence of production variables (labour arrangement) on system cash flow.

Keywords: Discrete Event Simulation; Factory Digital Twin; Financial metrics; Production demand; Labour resource planning.

1 Introduction

A significant volume of research has demonstrated the value of simulation to design and improve production systems. Much work has demonstrated the use of simulation to quantify system behaviour with new or changed system hardware, layout or control. Methods such as Discrete Event Simulation (DES) enable complex process chains to be examined. A key weakness of the current state-of-the-art in this area is the lack of non-engineering metrics typically modelled [1, 2]. For decision makers the critical metrics are often both production and financial. However automatically generating financial data from simulation output is a non-trivial task [2] with financial and production metrics typically dissimilar in fidelity and interval [1]. Thus this paper investigates a modelling approach representing both production and financial variables, in order to define data streams appropriate for monitoring and control interventions. This is achieved through the examination of a simple production problem (using the DES software QUEST) and the representation of the finances of a small production business (using Excel and typical accounting practice).

2 Literature review

A number of comprehensive, broad scope and focused review papers have been published which examine the use of DES in understanding and improving manufacturing systems [3-12]. These works have considered simulation software selection and evaluation [3-4]; manufacturing system design and operation [5-6]; scheduling and control [7-9]; system optimisation [10]; system maintenance [11]; and real-world applications considering manufacturing and business metrics [12]. Together these works provide an effective summary of progress in manufacturing modelling with DES over the last four decades. Predominantly what–if scenarios are considered, enabling the understanding of the effect of production variable changes on production output metrics; financial impact is frequently considered only indirectly through production metric such as throughput, cycle time, WIP etc. To date there are no procedures or guidelines proposed on how DES may be used to routinely assess the influence of operational level production variables on accounting metrics.

3 Case study and methodology

A modified production problem from the literature is modelled [13] to provide a platform for method development. The system creates two outputs and in its standard form includes part manufacture and assembly processes. Typically, the model assumes the processes as machining techniques that require little labour input. In the literature a single operator is required to conduct each process and each operator works on only one process. As labour has been less frequently studied in the literature herein all processes (A, B, C, D) are assumed as tasks with high labour content, Figure 1. Individual task setup times are incorporated into the process time and are assumed to be used for jig loading and fastener placement.

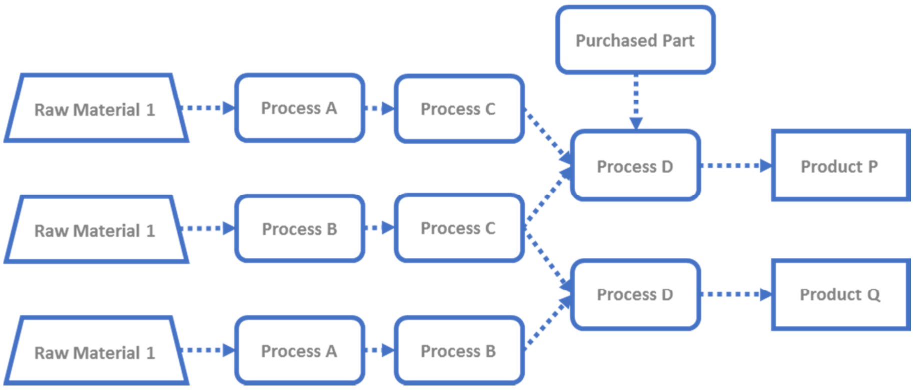


Fig. 1. Case study production arrangement (based on the P&Q problem).

The system produces two products (P's and Q's) to satisfy a demand with variability. One unit each of materials 1 and 2 combined with one purchased part constitutes the chain for product P. One unit each of materials 2 and 3 constitutes the chain for product Q. There are four processes in the system: A, B, C and D. Material 1 is processed by A, C and D, material 2 is processed by B, C and D and material 3 is processed by A, B and D. During process D product Q is made or the purchased part is added to create product P. In the defined problem process B is a constraint. Output from the first two processes are stored in the Manufacturing Component Stores (MCS) until either process D is free, the other product specific component reaches the MCS or the purchased part store is replenished. The product is then assembled and stored in the Final Goods Stores (FGS) before being shipped. The simulation model, Figure 2, represents each process with its own workstation within three distinct production lines: Processes A and C within Production Line 1 (PL1), Processes B and C within PL2, processes A and B within PL3, and process D as the Final Assembly workstation (FA). To govern the production system in the simulation a Material Requirements Planning (MRP) approach is employed. A weekly sales demand is employed to generate the backward schedule for the MRP. The system demand is calculated weekly based on an individual mean and standard deviation for both P's and Q's. This introduces a controlled level of demand variability into the model. Each simulation is run for an extended period of 24 months such that system behaviour can be considered as stabilised [2].

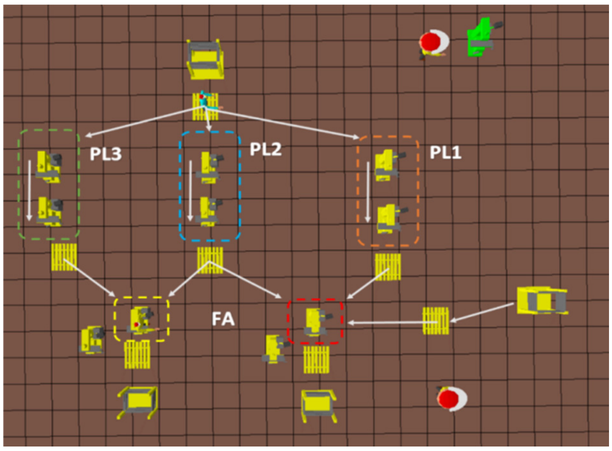


Fig. 2. Simulation model general layout.

In order to model the financial behaviour associated with the production process all activities resulting in financial transactions must be available from the simulation. Herein a prediction of an income statement which records the changes in financial position of a business over a defined period of time is of interest. The three main elements of an income statement are: Revenue – Income earned from trading; Gross profit – Revenue from trading less cost of goods sold (COGS); Net profit – Profit after all other income and expenses have been considered. From the production model the COGS can be calculated (including materials used to create goods sold and direct labour costs generated from the production of goods). With regards labour cost absorption costing is used which assigns the costs accumulated during the production process to individual products. This approach also enables indirect costs such as variable overheads and fixed overhead to be added to the direct material costs and assigned to the individual products. Moreover from the simulation WIP, MCS and FGS values are also available, describing not only the total system input and output with time but also the state of conversion at discrete time intervals.

The model variables are listed in Table 1. The variables of the model are grouped into several families. The cycle time inputs allow for the manipulation of the cycle time for each part at each process and the cycle time for the assembly of both products. The model represents stochastic failures in the form of a time delay of 15 minutes occurring every 150 parts for each of the machines. There is a set 5% rework value set within the overhead costing of the model. A stock cap is placed on the MCS for parts 1, 2 and 3 at a maximum capacity of 10 components. Labour is modelled as 3 or 4 operators with training for individual lines or all workstations. The noteworthy model simplifications and assumptions are: the model does not account for travel time between MCS and final assembly, and from final assembly to FGS.

Table 1. Simulation variables grouped into families.

Labour	Financial	Cycle Time	Variation
Number of operators	Standard cost of each raw material and purchased part.	Individual process cycle times.	Machine failure percentage.
Operator training (for individual lines or all workstations)	Amount of each raw material purchased per week.	Stock cap on stores (MCS, FGS)	Setup times for each part on each machine.
Operator breaks (UK legal worker breaks are modelled)	P and Q selling prices.		Scrap rate for each part on each machine.
	Wages and salaries.	.	
	Depreciation.		
.	Rent and rates per week.		

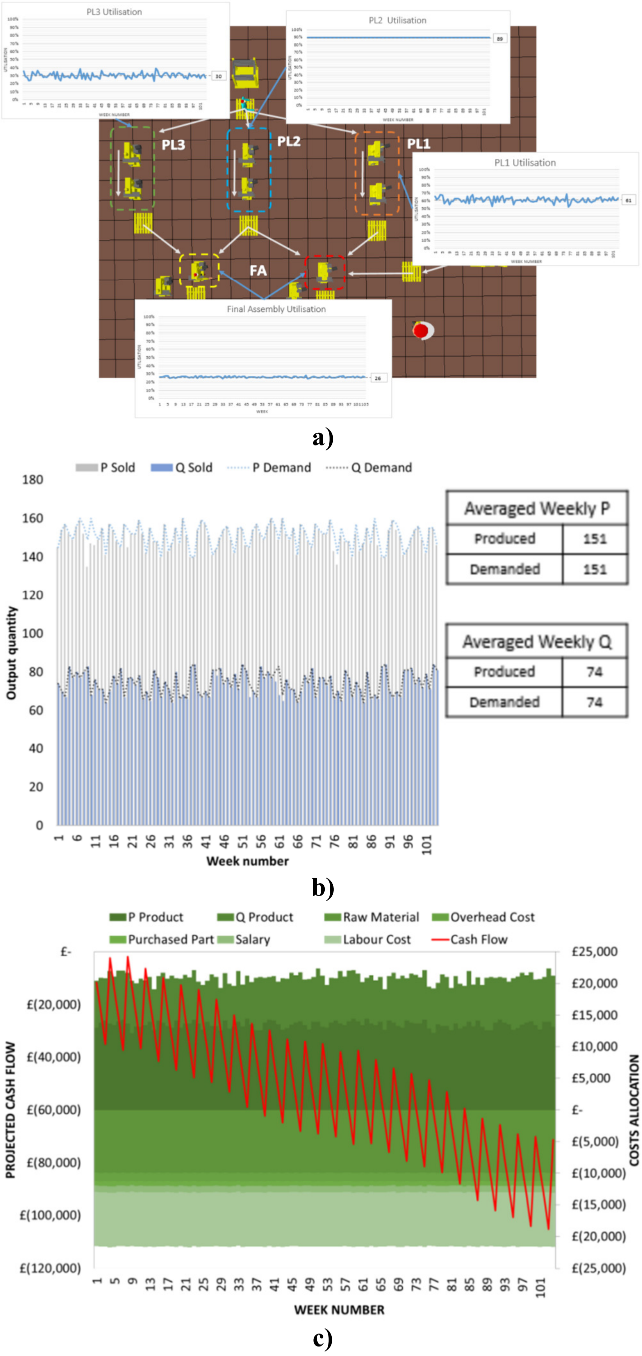
4 Results

A series of three simulations are examined with different labour provisions in order to demonstrate the simulation output and identify the key system characteristics. Each simulation has the same initial condition and the same demand profile for 24 months (P's: $\mu=151$, $\sigma=6$, Q's: $\mu=74$, $\sigma=6$). Each simulation has equal company financial arrangements (fixed costs (rent, rates, consumables, depreciation), variable costs (raw material, purchased part), payment schedules (debtor, creditor)), and equivalent individual process cycle times and process variability.

Dedicated operators on each work-station: Figure 3 presents the simulation output: part (a) illustrates work-station utilisation. In this case operator and work-station utilisation is the same thus PL1, PL2, PL3 and FA average utilisation is 61%, 30%, 89% and 26% respectively; (b) documents the units produced along with the units demanded; (c) plots the resulting system finances including the cash flow. Examining Figure 3(a) the average utilisation in PL2 is 89% representing the upper bound achievable with the modelled operator breaks. FA operator utilisation is only 26% and this represents the difference in maximum capacity of PL2 and this downstream process. Average utilisation in PL1 and PL3 is 61% and 30% respectively; with these utilisation levels a result of the FA constrained capacity and the presence of a buffer limit at the end of these lines (MCS buffer limit set to a maximum of 10 units). Thus as in the literature process B on PL2 is the system bottleneck. Examining Figure 3(b) the average produced and demanded units are the same, however closer inspection reveals a number of weekly instances of over and under production. Across the 24 months, there were 13 weeks with unsatisfied demand for product P and 5 for product Q. The financial predictions are plotted in Figure 3(c). In general, the cash flow has a negative trend with a final value of £ (71,279) at week 104. This reflects a high level of Labour and Overhead under recovery due to the low utilisation of both the workstations and operators in PL1, PL3 and FA, but also the reduced sales income resulting from the unsatisfied demand for both products.

Shared operator on PL1 and PL3 (three dedicated operators): As in the first simulation case PL2 and FA have dedicated operators but in this simulation case PL1 and PL3 have a single shared operator. Figure 4 presents the simulation output. In this case operator average utilisation for FA, PL1&PL3 and PL2 is 23%, 88%, and 89% respectively. Examining Figure 4(a) the average utilisation of PL2 and its operator remains high (on average 78%). Average utilisation of work-stations PL 1 and PL3 remain low (55% and 27% respectively) with their combined operator utilisation now 89% representing the upper bound achievable with the modelled operator breaks. Thus the shared operator on PL1 and PL3 appears to be a new system bottleneck. This is further evidenced by the reduction in system output. Across the period weekly output for Ps and Qs are 11% and 10% lower than the demand rate (Figure 4(b)). Demand of product P is unsatisfied for all 104 weeks and for 73 weeks for product Q. However the financial performance in Figure 4(c) presents a positive trending cash flow across the period with a final cash flow statement at week 104 of £98,915. Examining in detail the individual finance elements the impact of a lower level of Labour and Overhead under recovery, due to the higher utilisation of the operators, offsets the reduction in the number of goods sold.

Three floating operators: In the first two simulations the operators are assigned to individual production zones or work-stations. In this simulation three floating operators are modelled who can work on any production zone or work-station. The fixed and variable costs associated with labour were also modified to account for higher salary and training requirements. Figure 5 presents the simulation output. In this case operator average utilisation is 87%, 75% and 46%. Line and work-station utilisations have increased by between 3 and 6% over the preceding case with 3 operators with the same rank order of average utilisation with PL2 with the highest level and FA with the lowest. With respect to output, Figure 5(b), output again fall short of demand with unsatisfied demand in a total of 48 and 26 weeks for products P and Q respectively. Examining the financial performance, Figure 5(c), a positive trending cash flow is predicted with a final cash flow statement at week 104 of £ 121,948. Again the improved Labour and Overhead under recovery with higher utilisation and the greater volume of sales results in the positive cash flow and its final value.

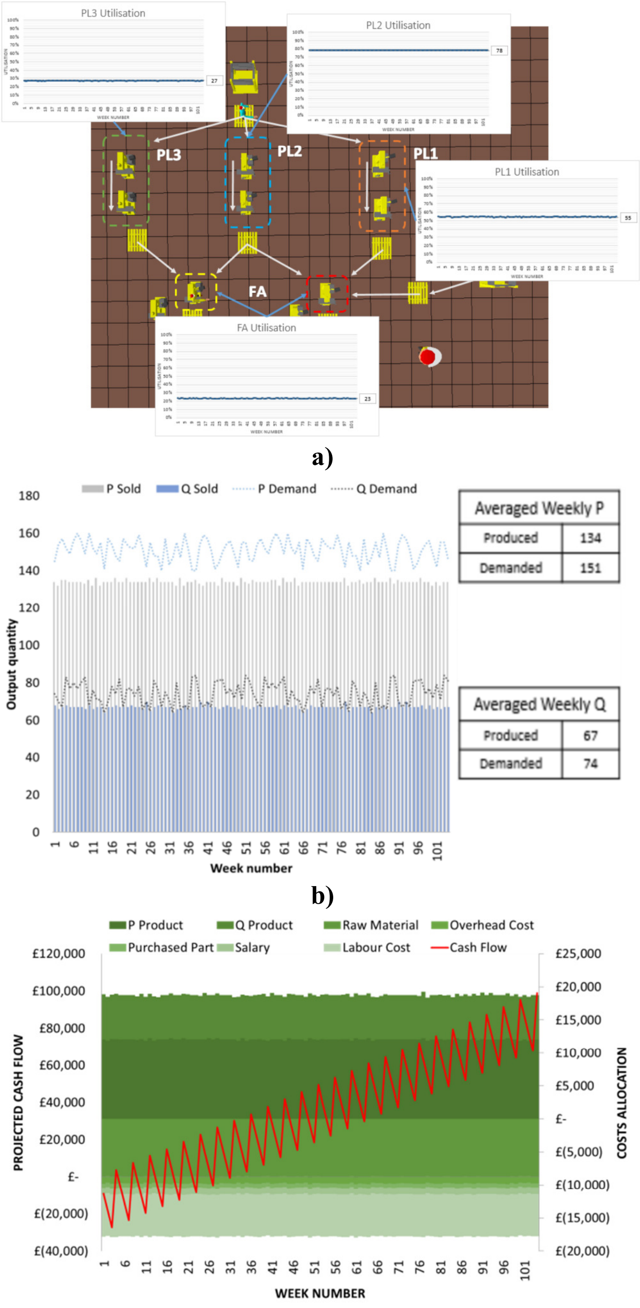


a)

b)

c)

Fig. 3. Dedicated operators on each work-station: (a) illustrates work-station and operator utilisation; (b) documents the units produced along with the units demanded; (c) plots the resulting system finances including the cash flow.



a)

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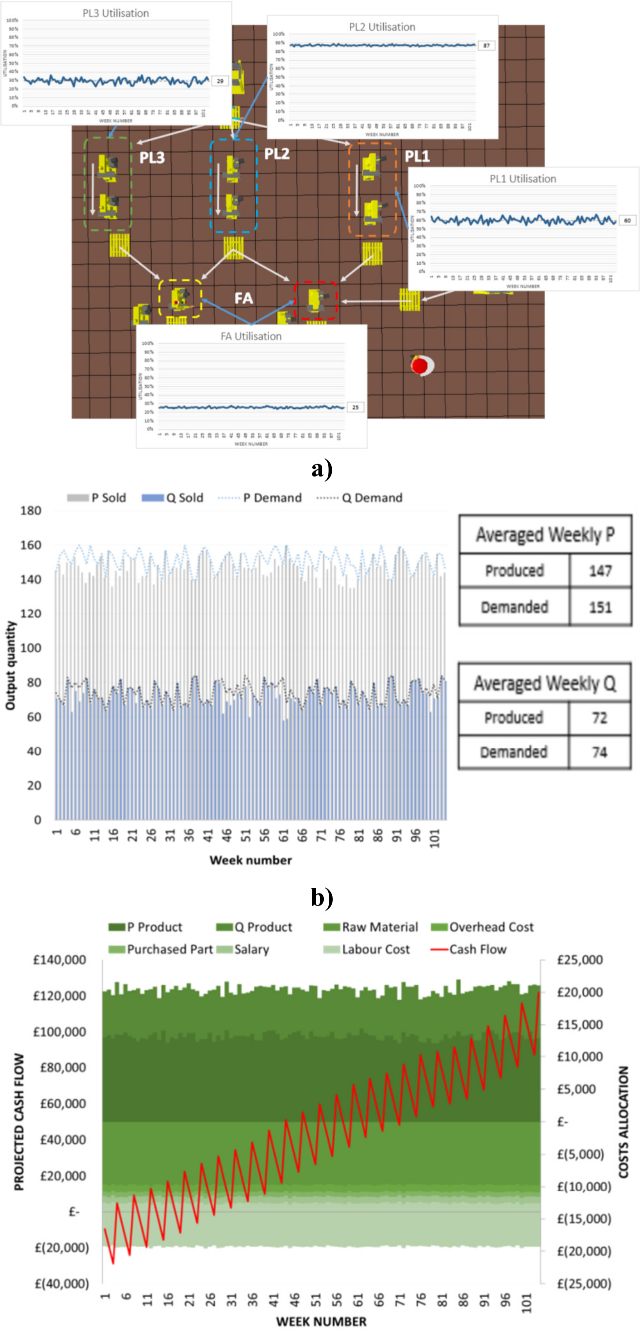
Fig. 4. Shared operator on PL1 and PL3 (three dedicated operators): (a) illustrates work-station and operator utilisation; (b) documents the units produced along with the units demanded; (c) plots the resulting system finances including the cash flow.



a)

b)

c)

Fig. 5. Three floating operators: (a) illustrates work-station and operator utilisation; (b) documents the units produced along with the units demanded; (c) plots the resulting system finances including the cash flow.

5 Discussion and Conclusions

Table 2 summarises the key simulation results. Four dedicated operators is the approach which best satisfies the demand rate but produces a generally negative cash flow. The next closest to the demand is three floating operators which achieved 3% less output for both products than the required demand rate but yielded the highest cash flow value at the end of the runtime due to the higher operator utilisation and product output. None of the operator arrangements modelled completely satisfies the specified demand thus a final simulation is undertaken with four floating operators. This arrangement of labour satisfies the specified demand with no unsatisfied demand weeks. However this arrangement consistently overproduces Ps and Qs each week and ultimately results in the largest negative final cash flow statement at week 104 of £ (233,496), Table 2. Although the system is arranged for one piece flow and production buffers set to minimise the opportunity for WIP to build up uncontrolled in the system there is no buffer limit on the FGS. Figure 8 presents FGS inventory costs and the clear overproduction for the system throughout the simulation period. Thus the challenge is to resource the production system to match the demand without overproduction. Doing this with the minimum number of operators will minimise the Labour and Overhead under recovery and thus maximise the final cash flow position.

Table 2. Simulation result summary.

	Average P Output	Average Q Output	Cash flow @wk. 104	% diff from P deman d (151)	% diff from Q deman d (74)	Total number of weeks in which P demand was unsatisfied	Total number of weeks in which Q demand was unsatisfied
4 dedicated operators	151	74	£(71,279)	0%	0%	13	5
3 dedicated operators	134	67	£98,915	-12%	-10%	104	73
3 floating operators	147	72	£121,948	-3%	-3%	48	26
4 floating operators	165	83	£(233,496)	10%	13%	0	0

Limited research exists on the use of simulations for the generation of coupled production and non-production data streams. Thus herein a simulation approach is proposed and demonstrated for coupled production and financial data generation for an idealised production system using DSE. The proposed approach enables the prediction of both operational production behaviour and higher level financial metrics (in the case study focusing on system labour arrangement and cash flow). The paper demonstrates how such modelling can enable assessment of specific production strategies which aim to influence both production and financial metrics. The modelling approach also represents the basic capability for simulation based control where real time production and financial data can be used as base conditions for future state prediction, again in both the production and finance domains.

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