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A MODEL TO STUDY DYNAMIC EFFECTS OF THE FORMATION OF DEFECTIVE ITEMS IN MANUFACTURING

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Abstract: In this work, a tool is developed to study operational aspects of manufacturing/production processes. Most studies of operations systems are concerned with waiting times, queue lengths, servers' utilization, etc. This work, on the other hand, is concerned with the yield of production/manufacturing processes with assembly operations in intermittent production environments. A novel approach is proposed to study operational effects of processes' imperfectness. Specifically, effects of the formation of defective items. The number of defective items and, hence, the number of conforming items that are formed in each execution of each activity in a process are random variables. The number of units of each component type in each (sub)-assembly is, however, dictated by the assembly ratios. Consequently, the actual numbers may not fit the planed targets or each other. These differences might be small but suffice to generate chaos in the system. A generic model is proposed, which enables to investigate and analyse these effects and evaluate tactics to handle them.

1 Introduction

This work is in the production/manufacturing domain. It is concerned with operational aspects of production/ manufacturing processes, which involve assembly operations, in intermittent production environments; e.g., batch processing. No specific system is studied but a generic model is developed to study operational effects of processes' imperfection. Specifically, the ramifications of the formation of defective items. To illustrate, consider a carmaker who receives a delivery of n wheels. Suppose $n = 4 \cdot k + m$ and $m < 4$. Then, since there are four wheels in a car, at least m wheels will remain unused, more, if k is greater than the desired number of cars. Further, if k is smaller than the desired number, a shortage is created despite the fact that at least m wheels remain unused. These miss-matches are created because the numbers of conforming units in production processes are random variables. The model proposed here is aimed at studying these miss-matches and their effects on systems' performances. This work differs from other studies in several manners. First, most stochastic models of operations systems, as defined below, are concerned with waiting times, queue lengths, servers' utilization, etc.; e.g., [1]. Second, serial processes are considered in most studies where inspections are included; e.g., the works reviewed in [2]. Third, long-range averages are examined; e.g. [3] and [4]. This study, on the other hand, is concerned with quantities – numbers of conforming and defective units in processes, which involve assembly operations, and is aimed at system dynamics and the examination of run-to-run relationships. Simulation is used because the quantities are random variables with complex relationships among them.

Widely used to define simulation is the term 'system'. Robinson [5], for instance, defines simulation, basically as "an imitation of a system" and many others; e.g., [6-8] also use this term. Law and Kelton [7] define a system "to be a collection of entities; e.g., people or machines that act and interact together towards the accomplishment of some logical end." Checkland [9] identified four main classes of systems: natural systems, designed physical systems, designed abstract systems and human activity systems. When people and machines interact, both human activity system and designed physical system are involved, and there are many examples of other combinations of Checkland's system types. Robinson [5] adopted Wild's [10] term *operations systems* or *operating systems* for systems where human activities are applied to physical entities, including production systems, service systems and supply chains.

As an imitation, any simulation builds on a model of the system it imitates and there are also distinctions between various types of models. In the context of this study, the relevant distinction is between static and dynamic (simulation) models. "A static simulation model is a representation of a system at a particular time, or one that may be used to represent a system in which time simply plays no role," while "a dynamic simulation model represents a system as it evolves over time." [7]

In operations systems time usually plays a primary role, either directly – the throughput time in manufacturing systems, waiting and service times in service systems, or indirectly by averaging over time – inventories, work in process, queue lengths, utilizations of servers, etc. Consequently, the vast majority of simulation studies of operations systems "track the system as it evolves continuously over time." ([8], p.3). The model developed in this study is different since it tracks the progress of units via the steps of the production process and through repeated executions the process. Although time passes as the units move forward and between process's executions, the proposed model is concerned with the numbers of units, the division between conforming and defective units and how these numbers are changed. Consequently, not times are sampled and the simulations are not discrete events simulations. Rather, the term Monte Carlo simulation, as defined by Law and Kelton [7], suits the present model. However, while Law and Kelton conclude that "Monte Carlo simulations are generally static rather than dynamic", the systems considered here have a dynamic nature because in an intermittent production environment distinct executions of a process are interrelated.

The model is generic in the sense that it models only the production process to which many other functions can be added; e.g., information management regarding residual quantities that are generated and can be used for future needs. Additionally, while production environments are considered here, the principle behaviour also suits service systems. In medicine, for example, erroneous diagnosis or imperfect treatment may result in the return(s) of the patient. Similarly, the failure of a student in a course forces her/him to repeat the course. In these cases, the patient or the student are, in many senses, analog to defective units in production systems.

2 The Skeleton of the Model

The model proposed here is built on an old tool – the *operations process chart* (OPC). Process charts were introduced by Frank and Lillian Gilbreth in 1921 [11]. From this early presentation emerged the OPC, which "is one of the most useful techniques in manufacturing planning. Actually, it is a 'diagram' of the manufacturing process. It has been used in many ways as a planning and control device. With the addition of other data, it can be extremely useful in manufacturing management." [12] The American Society of Mechanical Engineers established a standard for the OPC [13], of which the following symbols are used here: cycles represent operations and square boxes inspections, while arrows represent flows of material(s). Each task – operation, inspection, and so on, has an identification (ID) code. Usually, a list of all the tasks accompanies each OPC and provides additional information as proposed by Apple [12]: each task is briefly described, the performing station is identified, process and set-up times are specified, etc. This list is, called 'route sheet' and the tasks' IDs refer the OPC to the route sheet and vice versa. In this study, other additions, which are not included in the route sheet, are also considered.

An example OPC is illustrated in Figure 1. The operations in the figure are numbered from 0 to 15, while the inspections are numbered separately and in an opposite order to distinguish between the two groups. The arrows follow the direction of the process – from the elementary components to the end-item. The operations can be divided into two sub-sets: those that have a single entrance and those that have two or more entrances. A sequence of operations, each with a single entrance, represents a component – elementary or sub-assembly, of the final product. Operations with multiple entrances, on the other hand, represent assembly operations – the entering arrows correspond to the components of the assembly while the single leaving arrow is the assembled item – a sub-assembly or a final assembly. Operation #0 is the final assembly in Figure 1. Consequently, an OPC has a tree structure – at least one but maybe more arrows are directed to each cycle or square box, while only one arrow is directed away from any such entity. Any OPC with more than one end-item can be decomposed – one chart with a tree structure for each end-item. The activity in an arrowhead is the immediate successor of the activity in the arrow's tail.

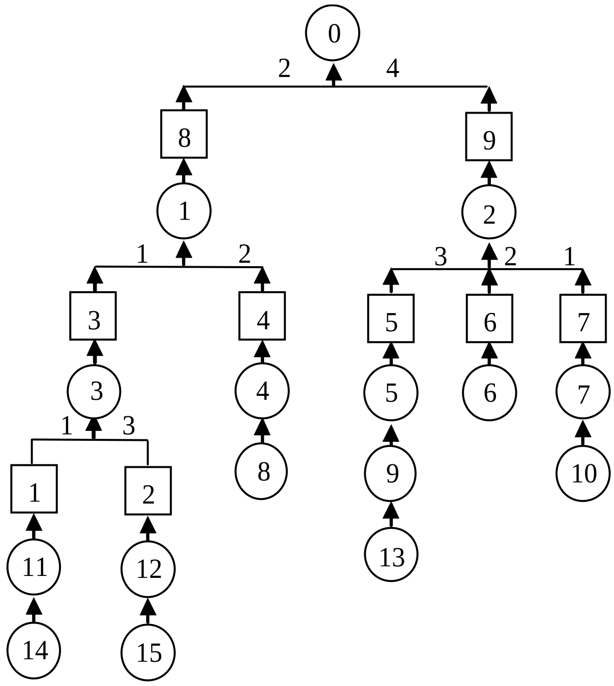

Figure 1 An Operations process chart with assembly ratios

Frequently, several units of the same component type are assembled in a single unit of the (sub) assembly; e.g., four wheels in a car, several processors in a multi-processor computer, etc. The number of units of a component type in its immediate (sub)assembly is its *assembly ratio*, which is the core input to material requirements planning (MRP). The assembly ratios are provided by the bill-of-materials (BOM); e.g., [14], and can easily be added to the OPC – on each link, which enters assembly operation, the corresponding assembly ratio is marked, as in Figure 1.

Another type of information is the corresponding probabilistic data: the defect rate of each operation and the error rates – of type I and type II errors, of each inspection. This information is necessary for many types of analyses as illustrated in the sequel, but has never been associated with the OPCs until the recent study of Eben-Chaime [15]. Once this information is added, the number of defective units that are generated in every pass through an operation and the resulting numbers of the inspections – type I and type II errors, can be sampled. Then, each process can be tracked step-by-step as explained in the following sections. Obviously, parallel execution of multiple processes can also be simulated, whenever desired.

3 Sampling

The novelty of the approach proposed here is to sample the required numbers individually and use the OPC to calculate the final outcome. These samplings are based on the following assumptions:

1) Independence between operations and inspections.
2) Independence between different operations.
3) Independence between item's units.

The first assumption is rather common; e.g. [16]. The second assumption is justified by the fact that each operation is performed in either a different station or on a different part and the third assumption follows the implicit assumption that the process is in control. Thus, defective units are formed only due to random causes; e.g., [17]. These three assumptions justify the applicability of the binomial distribution for all numbers and the use of the inverse transform algorithm; e.g., [8], p.56, for sampling. This method requires the number of trials, the success rate and a random number from a uniform (0,1) distribution, for each execution. The derivation of the numbers of trials and the success rates is the new component of the proposed approach and is detailed in the following sub-sections while the calculations of the final outcome are considered in the next section.

As noted, two types of entities are considered – operations and inspections and there is an inherent difference between these types. In inspections, units can be removed from the flow. A unit that is rejected does not continue with the other units – even if not wasted, a rejected unit should be repaired or reworked. The numbers of units is changed in operations, too, but not by removal. In any assembly, at least two component types or two units of the same type are assembled. Thus, the number of units that leave an assembly operation is no larger than any of the entering numbers.

3.1 Non-assembly Operations

Let d_i denote the mean defect rate of operation *i* and Q^{in}_{ij} are the numbers of conforming units that arrive to operation *i* in the j^{th} pass through it. Then, the number of new defective units, which are formed in this operation in this pass, x_{ij} is a binomial random variable with a success rate d_i and Q^{in}_{ij} trials. The number of conforming units that leave operation *i* in the j^{th} pass through it is: $Q^{out}_{ij} = Q^{in}_{ij} - x_{ij}$. Note that many more units that are defective can flow through operation *i* in the j^{th} pass because the numbers for each task depend also on previous tasks and the model keeps track of these numbers.

3.2 Assembly Operations

The defect rate of an assembly operation is not only its own defect rate, but of the arriving components, too, due to the mutual effects among the components, as demonstrated in [15]. Suppose an assembly consists of *K* component types, with assembly ratios m_k , $k = 1, \ldots, K$. Suppose also that Q_{ijk} conforming units and x_{ijk} defective units of component type *k* arrive to assembly operation *i* in the j^{th} pass through it. Then, the mean defect rate of assembly operation *i* in the j^{th} pass through it is:

$$1-(1-d_A)\cdot\prod_k\left[Q_{ijk}/\left(Q_{ijk}+x_{ijk}\right)\right]^{m_k} \qquad (1)$$

This is the binomial success rate for the sampling. Moreover, the number of trials for the sampling equals the number of units that can be assembled:

$$N_{ij} = min_k\left\{\left\lfloor Q_{ijk} + x_{ijk}/m_k\right\rfloor\right\} \qquad (2)$$

where ⌊x⌋ denotes the integer part of x. The generated binomial number, x_{ij} is the number of defective (sub) assemblies while $\min\{(Q_{ijk} +.x_{ijk})/m_k\}- x_{ij}$ is the number of conforming (sub) assemblies that are assembled. However, all assembled units including the defective units continue to the next step in the process.

Note that $(Q_{ijk} +.x_{ijk}) - m_k{\cdot}N_{ij} \geq 0$ units of any component type are not used by assembly operation *i* in the j^{th} pass through it. What happened to these units is influential on system's performance and the analysis of these effects motivated the development of the proposed model, as discussed in Sections 4 and 5.

3.3 Inspections

In inspections, as noted, units are removed from the flow. The removed units are of two types: defective units and conforming units, which are falsely rejected – error type I. On the other hand, not all defective units are detected and some slip through – error type II. Consequently, two numbers should be sampled and hence two (0,1) uniform random numbers – one for each error type are required. The rate of type I error, α, is the success rate and Q^{in}_{ij}, the number of conforming units that enter inspection *i* in the j^{th} pass through it, is the number of trials to determine the number of false rejections, f_{ij}, while $Q^{out}_{ij} = Q^{in}_{ij} - f_{ij}$ conforming units pass the inspection. In addition, x_{ij} defective units also pass the inspection. The type II error rate β and the number of defective units that enter inspection *i* in the j^{th} pass through it are used to sample this number, in a similar manner.

In Sum, both the number of conforming units and the number of defective units that travel each arrow in each pass through the OPC can be tracked as described above. This enables to determine the output – the number of conforming units of the end item that is produced from the specified input for each pass through the OPC.

4 System's Dynamics

Had only a single pass or a series of independent passes through the OPC been executed it would have been a static Monte Carlo simulation as defined by; e.g., Law and Kelton [7], but here, the execution of many passes is a key. A simulation which consists of a series of independent executions of the process – passes through the OPC would be very similar to stochastic analyses of projects where activities' durations are sampled to determine the project's critical path in each run; e.g., [18]. However, in intermittent production environments distinct process executions are not independent. Residual inventories might be constructed, as noted above, during each execution of the process due to the stochastic nature of the yields – the ratios of conforming units in production processes. These inventories turn the system into a dynamic system by interrelating distinct executions of the process as in each execution, units that were produced in earlier executions can be used and units that are produced now might not be used now and left for future use. Formally: $I_{i,j} = I_{i,j\text{-}1} + P_{i,j} – C_{i,j}$, where $I_{i,j}$ is the inventory at the end of the j^{th} execution of operation i, $P_{i,j}$ is the amount processed in operation i in its j^{th} execution and $C_{i,j}$ is the amount of units processed in operation i and consumed by subsequent operations. This is, actually, a well-known equation, which is used in dynamic production planning; e.g., [6, 10], but in production planning an index t for time periods is used instead of j, and here, the time intervals between successive executions of the process might be of different lengths.

Moreover, the inventories considered here can be constructed around assembly operations only: either before the assembly operations of sub-assemblies or after the final assembly. Production plans take into account the defect rate of each operation. Yet, the actual quantities are random numbers. Aiming at averages in long term planning, the maximal number of final assemblies should be assembled in each path. In some cases more than planned would be produced – adding to the inventory, while in other cases less than planned would be produced and the inventory can be used to fill the gap, keeping the average around the target. Maximal numbers should also be assembled of each sub-assembly, but miss-match between component types, as indicated above, can result in residual inventories. This includes cases where the number of arriving units is not an integer multiple of the assembly ratio of the corresponding component type. For example, of 23 wheels only 5 cars can be made with a residue of three.

Following this discussion, the number of units of each item which are not used in each pass through the process are rather small and vary from pass to pass. This creates a challenging inventory management task – where to keep, record keeping, etc., as illustrated in the next section.

5 Illustrative Runs

The purpose of this section is two-fold. First to illustrate the operation of the model and then to demonstrate some possible applications.

5.1 Model's operation

Table 1 portrays a single pass through the process of Figure 1 with no initial inventories. In the left column, the activities are identified: 'o' indicates operation, while 'i' indicates inspection and the numbers match the numbers in Figure 1. A mean defect rate of 1% is assumed for each operation, while mean rates of 3% for type I error and 2.5% for type II error are assumed for each inspection. (Obviously, the rates are equal just for simplification and different rates can be used just the same.) The second column lists the immediate successor of each activity and the assembly ratios are specified, were relevant, in the third column from the left.

Table 1 A single pass through the process

Ac. ID	Imm. succ.	Asse-mbly ratio	Number of defective units	Number of conform-ing units	Number of units not used
o0	--		11	994	5
i9	o0	4	1	4050	31
i8	o0	2	1	2009	0
o2	i9		49	4175	
o1	i8		31	2064	
i7	o2	1	4	4220	0
i6	o2	2	0	8458	10
i5	o2	3	15	12664	7
i4	o1	2	3	4188	1
i3	o1	1	1	2120	26
o7	i7		98	4352	
o6	i6	0	89	8722	
o5	i5		411	13089	
o4	i4		90	4360	
o3	i3		34	2180	
o10	o7	0	45	4405	
o9	o5		263	13237	
o8	o4	0	54	4396	
i2	o3	3	4	6654	16
i1	o3	1	1	2213	0
o13	o9	0	127	13373	
o12	i2		127	6873	
o11	i1		43	2277	
o15	o12	0	64	6936	
o14	o11	0	19	2301	

The three columns on the right side of the table are numbers of units, which were set aiming at the assembly of 1,000 conforming units of the end item, on average and accounting for both: the assembly ratios and the defect rates. (see [15]). Operations 6, 8, 10, 13, 14 and 15 are leaves in the *OPC* of Figure 1 – each has no arrow pointing into it. This is indicated by the '0' values in the assembly ratios of these operations, which thus serve as the starting points for the calculations. Material for 7,000 units enters operation 15, which constitutes the number of trials for this operation in this pass. Consequently, 64 defective units were sampled from the binomial distribution with 1% success rate (the mean defect rate), 7,000 trials and a cumulative probability which was sampled from the uniform (0,1) distribution. 2,320 trials were used for operation 14, 13,500 trials for operation 13, 4,450 trials for operations 8 and 10 and 8,811 trials for operation 6. The immediate successor of operation o15 is o12. The number of conforming units which enters this operation is 6,936 = 7,000 – 64 = the number of trials for sampling. 63 defective new units from this operation join the previous 64, 127 units together, leaving 6,873 conforming units. The numbers for o11, o9, o7 and o4 – the successors of o14, o13, o10 and o8 are determined in exactly the same way. The successor of o9 is o5. Hence, the number of trials for o5 are the 13,237 conforming units, which arrive to o5 from o9. Of these, 148 units turn defective, joining the 263 defective units that arrive from o9, too. The successors of o12, o11, o7, o6, o5 and o4 are all inspections.

For each inspection, two numbers should be sampled: the number of defective units that are missed and slip through the inspection and the number of false rejections. The details of o12 are used for the sampling for i2. False rejections are of conforming units. Hence, 6,873 trials are used for sampling with a success rate of 3% – the rate of type I errors. 219 conforming units are falsely rejected, leaving 6,654 to continue, with another 4 defective units, out of 127, which slipped through the inspection. Similarly, only 2,213 of the 2,277 conforming units that arrive to i1 continue, with the addition of a single defective unit. These principles are used also for the sampling of i4, i5, i6, and i7. The successors of all these inspections are assembly operations.

Recall the difference between operations and inspections, which is noted in the beginning of the third section. The total number of units is not changed while moving from o15 to o12, from o14 to o11, or in the other routes. In contrast, in the inspections the numbers are changed, due to the removal of units which are deemed defective.

In assemblies, the assembly ratios should also be taken into account. Going bottom-up, o3 needs to be considered first. In this operation, a single unit that arrives from i1 is assembled with 3 units from i2. The numbers of arriving units are 2,214 from i1 and 6,658 from i2 and since 2,214 < 6,658/3, only 2,214 units will be assembled and this is the number of trials for the sampling for operation o3. This also leaves 16 = 6,658 – 3·2,214 unused units at i2. The defect rates are 1/2,213 and 4/6,654, respectively for the arriving units from i1 and i2. Consequently, the defect rate of o3 is $1-0.99\cdot(2{,}213/2{,}214)\cdot(6{,}654/6{,}658)^3$, were 0.99 = 1- the self-defect rate of o3. The sampling resulted in 34 defective units and 2,180 conforming units. In o2, three component types are involved, which arrive from i5, i6 and i7. The number of trials is $4{,}224 = \min\{4{,}224, [8{,}458/2]^-, [12{,}679/3]^-\}$. Ten unused units are left in i6 and 7 units in i5. No defective unit arrive from i6. Hence, the defect rate of o2 is $1-0.99\cdot(2{,}213/2{,}214)\cdot(8{,}458/8{,}458)^2\cdot(12{,}664/12{,}679)^3$. Notice the numbers of residual units. 1 unit in i4 because the total number of units: 4,188 + 3 is odd and 26 units in i3, which suffice for additional 26 sub-assemblies, but have no matching components.

Table 2 A single pass through the process with final inspection

Ac. ID	Imm. succ.	Asse-mbly ratio	Number of defective units	Number of conform-ing units	Number of units not used
FI		1	0	996	0
o0	FI		11	1028	
i9	o0	4	1	4188	33
i8	o0	2	1	2077	0
o2	i9		50	4317	
o1	i8		32	2134	
i7	o2	1	4	4363	0
i6	o2	2	0	8735	1
i5	o2	3	15	13134	48
i4	o1	2	3	4330	1
i3	o1	1	1	2185	20
o7	i7		101	4499	
o6	i6	0	92	9008	
o5	i5		426	13574	
o4	i4		93	4507	
o3	i3		35	2247	
o10	o7	0	47	4553	
o9	o5		273	13727	
o8	o4	0	56	4544	
i2	o3	3	4	6844	2
i1	o3	1	1	2289	8
o13	o9	0	132	13868	
o12	i2		130	7070	
o11	i1		44	2356	
o15	o12	0	65	7135	
o14	o11	0	20	2380	

All the rules for the calculations have now been presented and the calculations up to the end-item continue in the same way. The final assembly – o0, ends up with 994 conforming units and 11 defective units. The corresponding outgoing quality is 994/ (11 + 994) ~ 98.9%

a bit higher than the mean value of 98.8%. Both values can be improved if a final inspection is added after the final assembly. The mean value of the outgoing quality increases to almost 99.97% and the results of the single pass with final inspection (FI) are listed in Table 2.
However, the additional inspection also involves 3% false rejections. Consequently, the input had to be increased by 1/(1-.03) – 1 ~ 3.1% in order to maintain the target of 1,000 conforming units. This is the sole source for the differences between Tables 1 and 2 – the same uniform (0,1) random numbers and the same mean defect rates have been used. Of course, however, with different numbers of units, the numbers of trials are changed and, in addition, the defect rates of the assembly operations. The final results reflects the improvement – while the same number of defective units, 11, have been assembled in o0, none slipped through the final inspection. The number of conforming units is about the same – the difference can be attributed to the modulo operator in the calculations of the assembly operations. This is also related to the different numbers of unused units.

5.2 *Systems' dynamics and possible applications of the model*

The development of the model was motivated by the desire to study the effects of the residual inventories – the unused units in Tables 1 and 2. To illustrate, a second pass through the process has been executed, with and without final inspection. These executions have been performed in two different settings. First, independent pass – the residues of the first pass have not been used in the second, and the residues of both passes are accumulated. Then, the residues of the first pass have been used in the second pass. The results are presented in Table 3. The passes without final inspections are shown on the top part, while the passes with final inspection are shown in the lower part, of the table. In the bottom of the table, the column titles are put in words. Non-assembly operations are excluded from the table since, as noted in the beginning of Section 3, the number of units is not changed in these operations.

Table 3 System's Dynamics

				First pass			2nd pass without residues				2nd pass with residues		
	ID	IS	AR	#D	#Conf.	I1	#D	#Conf.	I2	I1+I2	#D	#Conf.	I2
Without final inspection	o0			11	994	5	7	1002	9	14	7	1003	15
	i9	o0	4	1	4050	31	2	4035	1	32	2	4035	28
	i8	o0	2	1	2009	0	0	2020	2	2	0	2020	0
	o2	i9		49	4175		51	4165			51	4165	
	o1	i8		31	2064		23	2094			23	2094	
	i7	o2	1	4	4220	0	3	4213	0	0	3	4213	0
	i6	o2	2	0	8458	10	5	8478	51	61	5	8478	61
	i5	o2	3	15	12664	7	8	12734	94	101	8	12734	101
	i4	o1	2	3	4188	1	1	4233	0	1	1	4233	1
	i3	o1	1	1	2120	26	0	2119	2	28	0	2119	28
	o3	i3		34	2180		20	2178			20	2178	
	i2	o3	3	4	6654	16	3	6639	48	64	3	6639	64
	i1	o3	1	1	2213	0	2	2196	0	0	2	2196	0
With final inspection	FI			0	996	-4	0	1006	6	2	0	1008	4
	o0	FI		11	1028		7	1036			7	1038	
	i9	o0	4	1	4188	33	2	4172	2	35	2	4172	27
	i8	o0	2	1	2077	0	0	2089	3	3	0	2090	0
	o2	i9		50	4317		53	4306			53	4306	
	o1	i8		32	2134		23	2165			23	2166	
	i7	o2	1	4	4363	0	3	4356	0	0	3	4356	0
	i6	o2	2	0	8735	1	5	8756	43	44	5	8756	44
	i5	o2	3	15	13134	48	8	13204	135	183	8	13204	183
	i4	o1	2	3	4330	1	1	4376	1	2	1	4376	0
	i3	o1	1	1	2185	20	0	2193	5	25	0	2197	28
	o3	i3		35	2247		20	2254			20	2258	
	i2	o3	3	4	6844	2	3	6830	11	13	3	6830	1
	i1	o3	1	1	2289	8	2	2272	0	8	2	2272	4
	ID – activity identification IS – immediate successor AR – assembly ratio						#D – number of defective units #Conf. – number of conforming units Ix – residual inventory at the end of the xth pass						

System dynamics is manifested by the differences in the number of units; e.g., the differences between the column I2 of the independent passes – without residues, with I2 when the residues are used in the second pass. The most important consequence of the use of the residues is the increase in the yield of the second pass. With no final inspection one additional unit, while with final inspection two additional units of the end item are assembled. This also results in smaller inventories of the sub-assemblies – the total inventory at the end of the second pass in the rows of i8 and i9. No general conclusions can be drawn from a couple of passes, but the dynamic pattern is demonstrated and the model can be executed as many times as needed.

Noteworthy is the fact that the first pass, with or without final inspection ended with less than planned conforming units. Without final inspection, the 11 defective units, which continue to the next destination of this product, hide the problem, while the final inspection exposes this shortage, which may or may not be fulfilled by the surplus of the second pass. This type of behaviour, however, is certainly expected in reality and the proposed model enables to analyse its pattern and consequences.

6 Summary

Manufacturing/production processes are imperfect and produce defective items in a random manner. The introduction of inspections for quality assurance adds randomness to the system due to inspection errors of both types. The facts that product design dictates specific assembly ratios while the actual number of units that arrive to assembly operations are random numbers create miss-matches in production systems, which involve assembly operations. This might be less prominent when a single product is manufactured with rare interruptions for maintenance, but in a multiple-products-resource-sharing environment, which forces intermittent production, these miss-matches can result in chaos – quotas are not fulfilled and ordered are delivered either late or incomplete.

In this study, a dynamic simulation model has been developed to analyse these phenomena. It is dynamic because it enables to follow the interrelationships between different executions of production processes, focusing on residual quantities of items, which result from miss-matches, either surpluses or shortages. The operation of the model is described in details and its merit is demonstrated with few examples.

Since the magnitudes of these residual quantities are (often very) small compared to the total quantities, it is not even clear if they are managed in any form. The numerical examples show that even in two executions of a process using the residues of the first pass during the second makes differences. Much more significant differences are expected when processes are executed in the high frequency of industrial plants. The proposed model enables to better understand the behaviour of production systems and forms a basis for the evaluation of various approaches and tactics to improve system's performance.

References

[1] HÖPPE, N., SEEANER, F., SPIECKERMANN, S.: Simulation-based dispatching in a production system, *Journal of Simulation*, Vol. 10, No. 2, pp. 89-94, 2016. doi:10.1057/jos.2015.17

[2] REZAEI-MALEK, M., MOHAMMADI, M., DANTAN, J.-Y., SIADAT, A., TAVAKKOLI-MOGHADDAM, R.: A review on optimisation of part quality inspection planning in a multi-stage manufacturing system, *International Journal of Production Research* [Electronic], 2018. doi:10.1080/00207543.2018.1464231

[3] LI, J., BLUMENFELD, D. E., HUANG, N., ALDEN, J. M.: Throughput analysis of production systems: recent advances and future topics, *International Journal of Production Research*, Vol. 47, No. 14, pp. 3823-3851, 2009.

[4] MOHAMMADI, M., DANTAN, J.-Y., SIADAT, A., TAVAKKOLI-MOGHADDAM, R.: A bi-objective robust inspection planning model in a multi-stage serial production system, *International Journal of Production Research*, Vol. 56, No. 4, pp. 1432-1457, 2018. doi:10.1080/00207543.2017.1363425

[5] ROBINSON, S.: *Simulation: The Practice of Model Development and Use*, UK: Palgrave MacMillan, 2014.

[6] BANKS, J.: *Handbook of Simulation*, New York (NY): John Wiley & Sons Inc., 1998.

[7] LAW, AM., KELTON, WD.: *Simulation Modeling and Analysis*, 3rd ed., NY: McGraw-Hill Inc., 2000. (There are later editions only by Law, but for what appears in the early editions both authors deserve the credit.)

[8] ROSS, SM.: *Simulation*, 5th ed., Amsterdam: Academic Press, 2013.

[9] CHECKLAND, P.: *Systems Thinking, Systems Practice*, New York: John Wiley $& Sons Inc., 1981.

[10] WILD, R.: *Operations Management*, 6th ed., London: Thomson Learning EMEA, 2002.

[11] GILBRETH, FB., GILBRETH, LM.: *Process Charts*, The annual meeting of American Society of Mechanical Engineers, 1921.

[12] APPLE, JM.: *Plant layout and material handling*, 2nd ed., New York (NY): The Ronald Press Company, 1963.

[13] American Society of Mechanical Engineers, ASME *standard Operations and flow process charts*, New York (NY), 1947.

[14] NAHMIAS, S.: *Production and Operations Analysis*, New York (NY): 6th ed., McGraw Hill, 2009.

[15] EBEN-CHAIME, M.: Mutual Effects of Defective Components in Assemblies, *Journal of Manufacturing System*, Vol. 36, No.1, pp. 1-6, 2015.

[16] FRANCESCHINI, F., GALETTO, M., GENTA, G., MAISANO, D.: *Evaluating quality-inspection*

effectiveness and affordability in short run productions, In: Proceedings of the 2nd International Conference on Quality Engineering and Management, pp. 420-432, 2016.

[17] MONTGOMERY, DC.: *Introduction to statistical quality control*, 6th ed., New York (NY): Wiley, 2008.

[18] SHTUB, A., BARD, JF., Globerson, S.: *Project Management: engineering, technology, and implementation*. London: Prentice-Hall, 1994.