# Towards Modeling Changeovers for Flexible Foundry Manufacturing

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**Abstract**
Costs involved in implementing manufacturing flexibility to meet customer demand are more important in the SMEs, especially those that are labor intensive for example metalcasting companies located in a high cost country like Norway. Changeover is an important issue in foundries, and setup time of the dies is one of the vital parameters in the manufacturing process. This paper presents an analytical method for evaluating product changeover suitable for foundry manufacturing environment.

***Keywords***: Foundry Automation, Machine Flexibility, Product Handling Flexibility**.**

## 1. Introduction

The long term success of a foundry could be determined in a large part by its ability to institute and benefit from continuous improvement. What is lacking, however, are formal methods to guide this process. The goal of this paper is to gain insights which are useful on the manufacturing floor, and which can guide the process of continuous improvement. Hence, we will look into the system theoretic properties of the system, which in turn will warrant the studies. Typically, the process of continuous improvement is guided by management gurus, and discrete event simulations. Knowledge of the fundamental laws which govern the process of continuous improvement would be of great assistance.

Manufacturing system design and product quality have been studied extensively in the last fifty years. However, most studies address the problems independently. Majority of the publications in quality research seek to maintain and improve product quality and majority of the production system research seeks to maintain the desired productivity while ignoring quality. Little research attention has been paid to investigate the coupling interaction between product changeover and quality. However, it has been shown in [3] that product changeover and quality are tightly coupled. The analysis of this area, which is important but largely unexplored, will open a new direction of research to understand the flexibility of manufacturing systems to respond to varying customer demands. A foundry has time consuming changeovers and the machine capabilities can significantly affect part qualities and the final throughput at the end of the line. For example, in an iron foundry whenever the melt switches, the part aesthetic texture varies (Figure 1) which not only affects the part quality, but also the automated handling.

Fig. 1.a. Markers cast on corners on parts b. parts turned around (Note: Variation in dark and light regions on the part due to changeover of molten iron batch)

However, no analytical study has been found to investigate how flexibility (in terms of number of melt batches) impacts part quality, to enable throughput satisfaction and delivery requirements as well. Additional examples can be formed for paint quality, welding, and so forth. These examples suggest that flexibility and quality are tightly coupled and much more work is needed to fully understand this coupling. Such issue is of importance but almost neglected. The author believes that quality should be integrated into considerations when designing production systems as well as objectives of productivity and flexibility. One of the goals of this chapter is to investigate the coupling between flexibility and quality, and to provide foundry manufacturing automation engineers and decision makers, a better understanding of the quality implications in flexible manufacturing systems and provide some general guidelines for management of flexible operations. To start such a study, a simple aluminum foundry process structural model is created with the help of the participating company, and simplified using the aggregation technique.

## 2. Foundry Layout Investigation and Structural Model

The aluminum semi permanent mould (SPM) foundry was evaluated by breaking the equipment into five major systems. Those systems are the core machines, the castlines, the finish lines, the heat treat cells and the pre-machining line. Though each of these areas may include several machines or sub-systems, they will be evaluated as a department, based on the input and output information available from the plant.

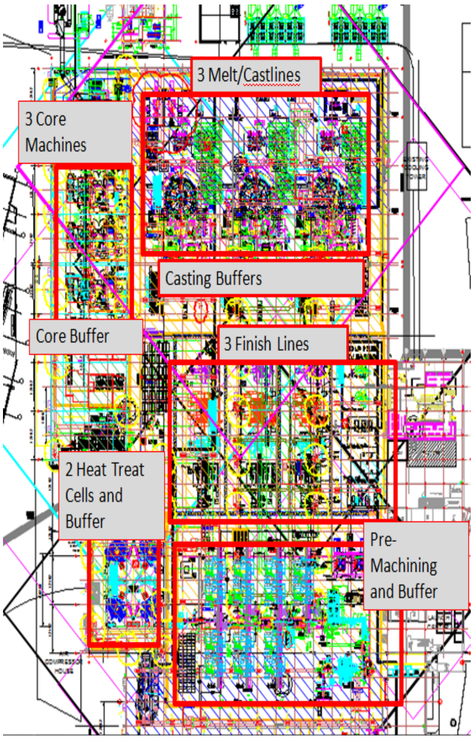


Fig. 2 SPM equipment layout, with separate departments highlighted

Shown below is the process flow for the SPM line:

- Sand cores are blown, unloaded, defined and loaded to buffer racks.
- Sand cores are sub-assembled at castline, set into molds, and castings are poured, then extracted.
- Castings go to finish lines where they are de-cored, de-rised and de-flashed.
- Castings go to heat treat area where they are put in ovens to achieve correct properties.
- Castings go to pre-machining line where they are further machined.

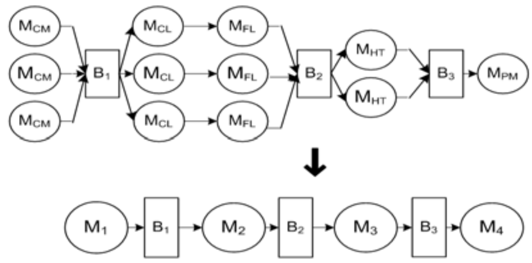


Fig. 3 A simplified model of the system

This original structural model captures each of the major machines or sub-systems.

Table 1: Machine number assignments for the original system structural model.

| ***Symbol*** | ***Description*** | ***Number of Machines*** |
|---|---|---|
| $M_{CM}$ | Core Machine | 3 |
| $M_{CL}$ | Cast Line | 3 |
| $M_{FL}$ | Finish Line | 3 |
| $M_{HT}$ | Heat Treat Cell | 2 |
| $M_{PM}$ | Pre-Machining | 1 |

The structural model shown above was simplified for analytical purposes using the aggregation procedure.

The results described in [2] can be utilized for analysis and design of production lines with unreliable machines. As far as the analysis is concerned, the formulas obtained give the leading order terms for manufacturing line performance characteristics. From the results derived, it follows that the calculation of production rate for manufacturing line with geometric machines with Bernoulli quality model becomes too complex beyond the simple two machine one buffer simplification, and simulation tools may prove beneficial in such case.

## 3. Foundry Changeover Flexibility and Quality Coupling

### 3.1 One Part Type Manufacturing

Consider a flexible manufacturing system producing one part type and let *a* and *na* denote the states of the system producing a acceptable part or a defect (not-acceptable) part in steady states, respectively. Note, that here we do not consider machine breakdowns and only machine running times. When a system is in state *a*, it has transition probability $\alpha$ to produce a defective part in the next cycle, and probability $1-\alpha$ to continue producing a good part.

Likewise, when the system is in state *na,* it can produce a good part with probability β and a defective part with probability *1-β* in the next cycle. *P* and *R* can be viewed as *missed opportunity for quality* and *repair probabilities* respectively. Similar to production rate analysis, constant transition probabilities are assumed to simplify the analysis for steady state operations.

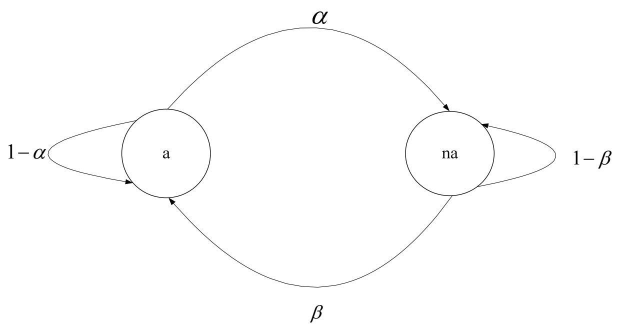


Figure 4 State transition diagram in one-product type case

Let *P(a,t)*and *P(na,t)*denote the probabilities that the system is in states *g* or *ng* at cycle *t* ,respectively. As one can observe, states *a* and *na* are similar to the up and down states in production rate analysis. Therefore, extending the work in production rate analysis to study quality performance, we obtain

*P(a,t+1)=P(produce an acceptable part at t+1| produce an acceptable part at t)P(a,t)+P(produce an acceptable part at t+1| produce an un-acceptable part at t)P(na,t)*

$$= P(a,\ t+1/a,t)P\left(a,t\right) + P(a,\ t+1/na,t)P\left(na,t\right)$$
$$= \left(1-\alpha\right)P(a,t) + \beta P(na,t).$$

In terms of steady states, *P(a)* and *P(na)*are used to denote the probabilities to producr an acceptable or un-acceptable part during a cycle, respectively, that is,

$$\lim_{t\to\infty} P(a,t) := P(a)\,,\ \lim_{t\to\infty} P(na,t) := P(na)\,.$$

It follows that

$$P\left(a\right) = \left(1-\alpha\right)P(a) + \beta P(na)$$

Which implies

$$P(na) = \frac{\alpha}{\beta} P(a)\,.$$

From the fact that total probability equals 1,

$$P(na) + P(a) = 1\,,$$

It follows that the system acceptable part ratio is

$$P(a) = \frac{\beta}{\alpha+\beta}\,.$$

As expected, *P(a)* above has a similar from as machine efficiency. Below we extend this study to multiple-product-type case.

### 3.2 Two Part Type Manufacturing

Now we consider a flexible machine manufacturing two types of products, type 1 and type 2. Consider $P(a_i)$ and $P(na_i)$ as the probabilities to produce an acceptable part type $i$ , $i = 1\,,\ 2$ , during a cycle, respectively. Again $P(a_i)$ and $P(na_i)$ are used to represent the acceptable or un-acceptable component probability (of both parts). Then we obtain

$$P(a_1) + P(a_2) = P(a)\,,$$

$$P(na_1) + P(na_2) = P(na)\,.$$

Additionally, introducing the following assumptions.

(i) A flexible manufacturing system has four states : producing an acceptable part type 1, and type 2, denoted as $a_1$ , $a_2$ , $na_1$ and $na_2$ , respectively.

(ii) The transition probabilities from acceptable states $a_i$ , $i = 1\,,\ 2$ ,to un-acceptable state $na_j$ , $j = 1\,,\ 2$ ,are determined by $\alpha_{i,j}$ .The system has probabilities $\nu_{i,j}$ to stay in an acceptable state $a_i$ , $i = 1\,,\ 2$ . Similarly, when the system is in an un-acceptable state $na_j$ , $j = 1\,,\ 2$ ,it has probabilities $\beta_{i,j}$ to transit to an acceptable state $a_i$ , $i = 1\,,\ 2$ , and probabilities $\eta_{i,j}$ to stay in un-acceptable states $na_j$ , $j = 1\,,\ 2$ .

Similar to single product case, $\lambda_{ii}$ and $\mu_{ii}$ , $i = 1\,,\ 2$ ,can be seen as *non-switching part quality failure* and *repair rate* probabilities, respectively (i.e. product types are not switched). Analogously, $\alpha_{i,j}$ and $\beta_{i,j}$ , $i\,, j = 1\,,2\,, i \neq j$ ,

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can be seen as switching quality missed opportunity and repair rates, respectively.

Based on the above assumptions, we can describe the system using geometric model [2]. In addition, since total probabilities equal 1, we have

$P(1)+P(2)=1$ , $P(a_1)+P(na_1)=P(1)$ , $P(a_2)+P(na_2)=P(2)$ ,

$\alpha_{11}+\alpha_{12}+\nu_{11}+\nu_{12}=1$ , $\alpha_{22}+\alpha_{21}+\nu_{22}+\nu_{21}=1$ , $\beta_{11}+\beta_{12}+\eta_{11}+\eta_{12}=1$ , $\beta_{22}+\beta_{21}+\eta_{22}+\eta_{21}=1$ .

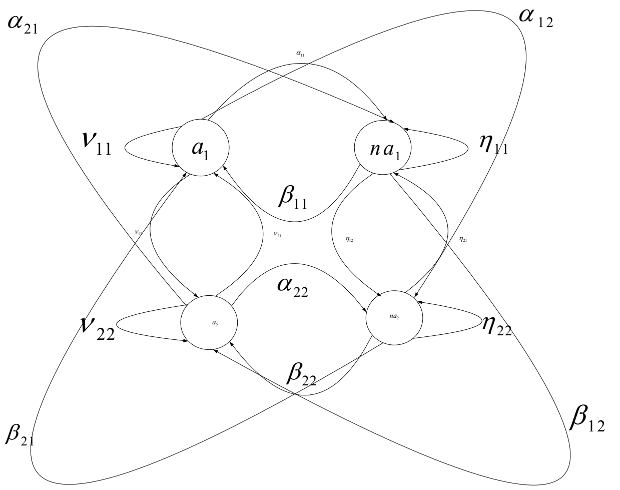


Figure 5 State transition diagram in two –part scenario

Similar to the case of one part type, the transition to state $a_1$ can be described as

$$P(a_1,t+1)=P(a_1,t+1|a_1,t)P(a_1,t)+P(a_1,t+1|na_1,t)P(a_1,t)+P(a_1,t+1|a_2,t)P(a_2,t)+P(a_1,t+1|na_2,t)P(na_2,t)$$

=

$$\nu_{11}P(a_1,t)+\nu_{21}P(a_2,t)+\beta_{11}P(na_1,t)+\beta_{21}P(na_2,t)$$

Considering the steady state probability $P(a_1)$ , we have

$$P(a_1)=\nu_{11}P(na_1)+\nu_{21}P(na_2)+\beta_{11}P(na_1)+\beta_{21}P(na_2)$$

Similarly,

$$P(a_2)=\nu_{12}P(a_1)+\nu_{22}P(a_2)+\beta_{12}P(na_1)+\beta_{22}P(na_2)$$

$$P(na_1)=\alpha_{11}P(a_1)+\alpha_{21}P(a_2)+\eta_{11}P(na_1)+\eta_{21}P(na_2)$$

$$P(na_2)=\alpha_{12}P(a_1)+\alpha_{22}P(a_2)+\eta_{12}P(na_1)+\eta_{22}P(na_2)$$

Solving the above equations, we obtain a closed formula to calculate the probability of good quality part $P(g)$ .

### 3.3 Multiple (n>2) Part Types

Considering flexibility in manufacturing systems, and using the same notations as above for depicting *i*=1,…,*n* product types. Therefore, we have

$\sum_{i=1}^{n}P(i)=1$ , $\sum_{i=1}^{n}P(a_i)=P(a)$ , $\sum_{i=1}^{n}P(na_i)=P(na)$ ,

$P(a_i)+P(na_i)=P(i)$ , *i=1,…,n,*

$\sum_{i=1}^{n}P(a_i)+\sum_{i=1}^{n}P(na_i)=1$ ,

$\sum_{j=1}^{n}(\alpha_{ij}+\nu_{ij})=1$ , *i=1,…,n,* $\sum_{j=1}^{n}(\beta_{ij}+\eta_{ij})=1$ , *i=1,…,n,*

Similar to the procedure in the previous section, the transition equation is obtained:

$$P(a_j)=\sum_{i=1}^{n}\nu_{ij}P(a_i)+\sum_{i=1}^{n}\beta_{ij}P(na_i)$$ *,j=1,…..,n*

$$P(na_j)=\sum_{i=1}^{n}\alpha_{ij}P(a_i)+\sum_{i=1}^{n}\eta_{ij}P(na_i)$$ *, j=1,….,n-1,*

$$1=\sum_{i=1}^{n}P(a_i)+\sum_{i=1}^{n}P(na_i)$$ .

Written as a matrix form, $AX=B$ ,

Where,

A=

$$\begin{pmatrix} \nu_{11}-1 & \nu_{21} & \ldots & \nu_{n1} & \ldots & \beta_{11} & \beta_{21} & \ldots & \beta_{n-1,1} & \beta_{n,1} \\ & \vdots & & & \ddots & & & \vdots & & \\ \lambda_{1,n-1} & \lambda_{2,n-1} & \ldots & \lambda_{n,n-1} & \ldots & \eta_{1,n-1} & \eta_{2,n-1} & \ldots & \eta_{n-1,n-1}-1 & \eta_{n,n-1} \\ & 1 & 1 & \ldots & \ldots & \ldots & \ldots & \ldots & 1 & 1 \end{pmatrix}$$

$$X=(P(a_1),P(a_2),...,P(a_n),P(na_1),P(na_2),...,P(na_n))^T$$

,

$$B=(0,0,...,1)^T$$ .

Hence, the following

*Theorem*
Under assumptions (i) and (ii) the acceptable part probability can be calculated from

$$P(a)=\sum_{i=1}^{n}P(a_i)=\sum_{i=1}^{n}x_i ,$$

where $x_i = P(a_i)$ , *i=1,..., n* are the elements in X and can be solved from

$$X = A^{-1}B$$

and A and B have been defined above.

From [3] we know that matrix A is invertible due to the fact that an irreducible Markov chain with finite number of states has a unique stationary distribution. In case of 'similar batch components', i.e., *n* product types are equally manufactured (batch) and have identical transition probabilities, we have

$$\beta_{11}=\beta_{ii} , \quad \nu_{11}=\nu_{ii} , \quad \alpha_{11}=\alpha_{ii} , \quad \eta_{11}=\eta_{ii} ,$$

*i=1,…,n.*

$$\beta_{12}=\beta_{ij} , \quad \nu_{12}=\nu_{ij} , \quad \alpha_{12}=\alpha_{ij} , \quad \eta_{12}=\eta_{ij} ,$$

*i=1,…,n.*

Which implies that transition from one component to another is equivalent in terms of quality. The corollary below follows

*Corollary 1:*
Under assumptions (i) and (ii), the acceptable part probability *P(a)* for *n* batch parts could be described by

$$P(a)=\frac{\beta_{11}+(n-1)\beta_{12}}{\alpha_{11}+\beta_{11}+(n-1)(\alpha_{12}+\beta_{12})}$$

*P(g)* is monotonically increasing and decreasing with respect to $\beta_{1i}$ and $\alpha_{1i}$ , i=1,2, respectively.

## 4. Discussion and Future Work

Similar to production rate analysis [2], let

$$e_{1i}=\frac{\beta_{1i}}{\alpha_{1i}+\beta_{1i}} , \; i=1,2,$$

Where $e_{12}$ and $e_{11}$ denote the represents the efficiency to produce an acceptable part if part type is kept constant (*i=1*) or changed (*i=2*).

*Corollary 2:*
Under assumptions (i) and (ii) the following holds for the batch part type case:

$$P(a)=\frac{\beta_{11}}{\alpha_{11}+\beta_{11}} \text{ if } e_{11}=e_{12} ,$$

$$P(a)<\frac{\beta_{11}}{\alpha_{11}+\beta_{11}} \text{ if } e_{11}>e_{12} ,$$

$$P(a)>\frac{\beta_{11}}{\alpha_{11}+\beta_{11}} \text{ if } e_{11}<e_{12} .$$

The expression from corollary 1 can be rewritten as

$$P(a)=\frac{\beta_{11}+(n-1)\beta_{12}}{\frac{\beta_{11}}{e_{11}}+(n-1)(\frac{\beta_{12}}{e_{12}})}$$

$$=\frac{\beta_{11}+(n-1)\beta_{12}}{\beta_{11}+(n-1)\beta_{12}(\frac{e_{11}}{e_{12}})} .$$

The above corollary implies that when $e_{11}=e_{12}$, which means that quality efficiency doesn't change whether the component type production is changed , we can obtain *P(a)* with the same method as in one component case. However, if $e_{11}>e_{12}$, which means changeover quality efficiency is decreased then the introduction of a new component will lead to a decrease in system quality performance. Finally, a flexible manufacturing system can perform better on different components in terms of quality only when the changeover quality efficiency is improved with additional components, that is, $e_{12} > e_{11}$. Since much more effort may be needed (for changeover) to keep $e_{12}$ same or larger than $e_{11}$, using a batch operation to reduce product transitions helps as an alternate solution to the multiple product environment, to keep manufacturing flexibility.

Changeover is an important issue in foundries, and setup time of the dies is one of the vital parameters in the manufacturing process. The set of manufacturability rules specifically for foundry automation had been proposed in [4], to enable shorter set up times in a production environment. Efforts were made to sustain the existing and proposed on the basis of Poka Yoke principles.

## 5. Conclusions

The work presented in this paper lays a foundation for a possible approach for further investigation of the coupling between flexibility and product quality. The future work can be directed to, first extend the model to multistage flexible lines; second, evaluate the impacts of different scheduling policies on quality; third, integrate with online and offline inspections, quality repairs, and maintenance scheduling and so forth; integrate with multiple-product throughput analysis models with quality control devices and study tradeoffs among productivity, quality, and order delivery; and finally, apply the method to model and analyze different flexible manufacturing systems. The results of such study will provide manufacturing engineers and managers a better understanding of the quality implications and to summarize some general guidelines for operation management in flexible manufacturing systems.

The mathematical proofs are available from the author on request.

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