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ENHANCING RELIABILITY OF A CONTINUOUS MANUFACTURING SYSTEM USING WIP BUFFERS

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Abstract
Continuous Manufacturing System (CMS), usually employed for mass production, has a serial line arrangement of different machines. These are arranged in sequence of operations to produce a specified product. In such CMS, over long period of usage, the production rate comes down, due to failures of machines in the line. Thus, reliability i.e. probability that such a CMS will give rated production over a year reduces considerably. To compensate for such loss of production, introduction of redundant parallel standby machines approach has been hypothesized and is in use irrespective of cost involved. A new approach of introducing buffers of Work-In-Progress (WIP) at various stages in the line, in place of standby redundant machines, has been proposed and its effect on the reliability of CMS to give rated production is analyzed. The results show that by using the proposed system/approach, the reliability that such a CMS will give rated production, is 100 %.
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Key Words: Continuous Manufacturing System, Reliability, Standby, Buffer, Work-In-Process, Configuration

1. INTRODUCTION

In a conventional continuous manufacturing system, machines are arranged in series as per the sequence of operations. This type of arrangement or configuration is also known as Serial Line Arrangement and is deployed for mass production purposes. The layout of such arrangement is termed as product layout. This is well illustrated by the Fig. 1.

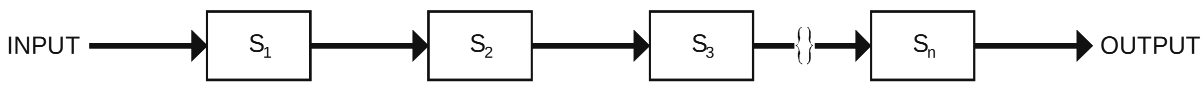

Figure 1: Configuration illustrating Product Layout (conventional serial line arrangements of machines).

Such types of configuration of production line have got specific features and are designed to give specific advantages:

- In a conventional continuous manufacturing system, machines are arranged in series as per sequence of operations. This is being illustrated in Fig. 1, i.e. output from stage 1 is input at next stage 2 and so on.
- Least material handling cost and damages.
- Frequent change over and adjustments of sub-system will practically be not there and hence initially great economy of production.
- Consistency of quality of output.

They are mostly line balanced i.e. output from stage I sub-system in quantity equals the input to stage II sub-system and so on, till the end product. This way WIP logistics is optimized. However, in real life situation, such configuration of machines does not produce the designed quantity of output *P*. There are many reasons attributed to this. Main reasons can be: (a) Initially, there are teething troubles in stabilizing the production system as a whole. (b) Failure of logistics of materials supply. (c) Sometimes poor quality of raw material affects the WIP flow of materials between the stages of production. (d) System as a whole is not getting operated or maintained due to lack of full knowledge or training and skill on the part of Engineers/Operators. (e) Actual working conditions are quite different than the designed conditions. (f) Lastly and ***most importantly*** is the failure of the machine or sub-system at any stage, due to which if any machine or sub-system in the production line fails, then the entire CMS stops producing, hence loss of production or output. And greater is the downtime greater is the loss of production.

1.1 Drawback of conventional CMS

This specific feature of CMS i.e. if any machine or sub-system in the line fails, then the entire production line stops producing, this is quite obvious, because there will be no supply of WIP from failed sub-system to next stage sub-system and onwards in the line. This way the output from the CMS comes down. Moreover, as the machines or sub-systems become older and older, with continuous usage of time, then the failure rate of each machine and thereby that of CMS increases. In all such situations, efforts are put to combat such situations so as to achieve production to the norms of rated capacity. All such efforts are mostly on crises basis. As stated above, when sub-systems become older and older, the probability of getting production to the level of rated capacity reduces considerably. Failure rates of sub-systems increases, mean time between failures of each sub-system reduces and at the same time, mean time to repair increases, all contributing to the reduced availability of the system and in turn results in loss of direct and indirect manpower hours at various sub-systems, loss of machine hours and related facilities and unnecessarily cost built ups of overheads and finally loss of business and company’s reputation too. Also extra efforts are required to combat the situation on crises basis i.e. fire fighting at much higher cost.

1.2 Areas of attack

As such one has to find out rather invent ways and means practically to enhance availability of the system over time *T* (may be taken over the year). In general, the availability of a system is a complex function of reliability, maintainability and logistic and administrative effectiveness. This can be expressed as narrated in book on reliability analysis by [1], where:

A_s - System availability i.e. probability that system will be available for use over time *T* (whenever required).

R_s - Total System Reliability i.e. probability that a system will be functional and will be able to produce required quantity of products over time *T*.

t - Meantime to repair.

M_s - System’s maintainability i.e. probability of repairing in time *t*.

L - Logistic & Administrative Effectiveness.

2. LITERATURE SURVEY

Taking cognizance of this drawback of CMS, extensive literature survey was made to see that what efforts have been made in the past by the researches in this particular area of concern. It has been observed that maintainability and logistic aspects do take care of availability of the system such that its availability is maximized. However, these efforts do not have appreciable affect on improvement of availability of the system. Most important aspect is the reliability of the system which affects the availability of the system most appreciably. Hence, efforts have been made to enhance reliability of the system/sub-system. In recent literature survey, it has been observed that conventional approach of increasing reliability of the system has been used. What has been suggested by [2-7], in their contributions is that the manufacturing system configuration (Serial Line Arrangements) heavily influence performance, capacity and reliability, and as such they have suggested that a manufacturing system can be designed (arranged) in many configurations, for example serial, parallel or hybrid (a combination of serial & parallel). A parallel configuration has multiple identical part flow paths as shown in Fig. 2 (a), (b) or (c). A hybrid configuration is a mix of serial and parallel configuration. These types of machine layouts can well be conceptualized.

At University of Michigan [8], a research centre for reconfigurable machining system has been established, where impact of reconfigurations is getting studied from various angles to see the affects on performances. Few more contributions have been made, in this context [9-11] and these are also in line with the above approaches. In a recent paper [12] what has been considered is a repairable production unit, subject to random failures, which supplies input to a subsequent assembly line operating according to a just-in-time configuration. Preventive maintenance actions are regularly performed on the production unit at instants t, $2t$, $3t$ etc. The corrective and preventive maintenance actions have random durations. In order to penetrate perturbations caused by breakdowns and by planned maintenance actions, a buffer stock is built up to ensure the continuous supply of the assembly line at a constant rate R. To buildup this buffer stock, the minimum production from each sub-system is at rate $R = p + \beta$, i.e. production rate at each stage more than the rated capacity and hence heavy initial cost and thus at a higher cost of production. Thus there is still scope to explore alternatives such that reliability and thereby availability of a continuous manufacturing line for production increases considerably, that too at least cost and ultimately rated capacity of production over time T is achieved.

3. THE NEW APPROACH

Taking cognizance of all these and also considering the cost aspects, a new approach has been conceptualized in this work/paper which suggests that instead of keeping standby sub-systems in parallel at any or all stages, reference to Fig. 2 (a), (b), (c), better to introduce/keep buffers of Work-In-Process of required type, quality and quantity at each stage of production, much similar to standby parallel sub-system, reference to Fig. 3 (a), (b), (c). And whenever any sub-system fails, then that time to supply output from this failed sub-system stage to next stage from the buffer of WIP (semi-finished product) being kept at that sub-system and thus to maintain continuity of supply to next sub-system and thus maintain continuity of manufacturing at rest of the sub-systems and that of a CMS as a whole.

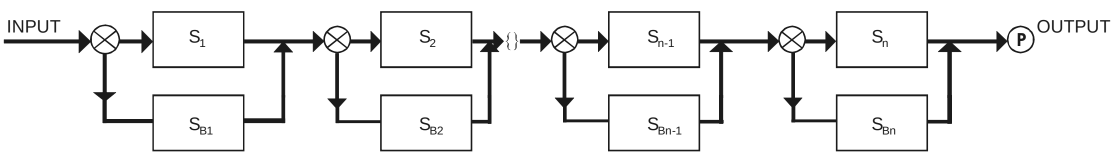

Figure 2 (a): Configuration under parallel standby redundant arrangement (first type).

Note: S_i – sub-system i, S_{Bi} – standby sub-system i, ⊗ – flow diverter (in all figures).

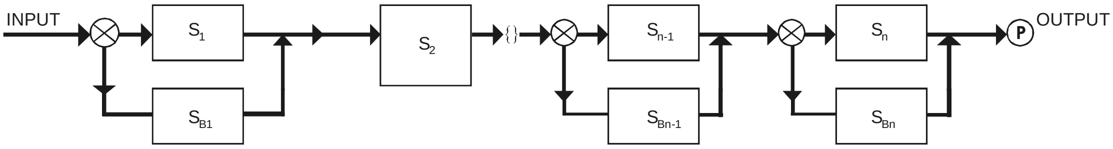

Figure 2 (b): Configuration under parallel standby redundant arrangement (second type).

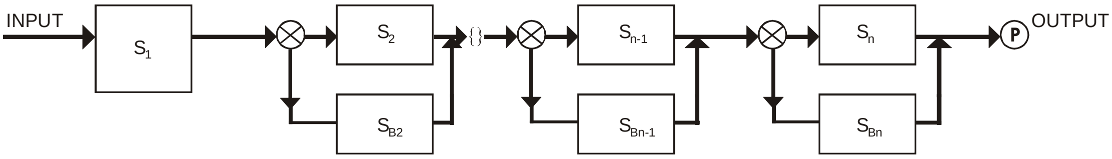

Figure 2 (c): Configuration under parallel standby redundant arrangement (third type).

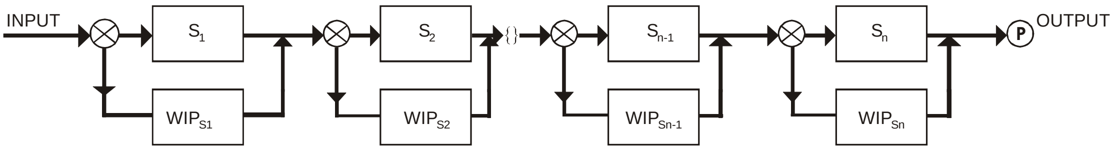

Figure 3 (a): Configuration under proposed approach of keeping WIP buffers (first type).

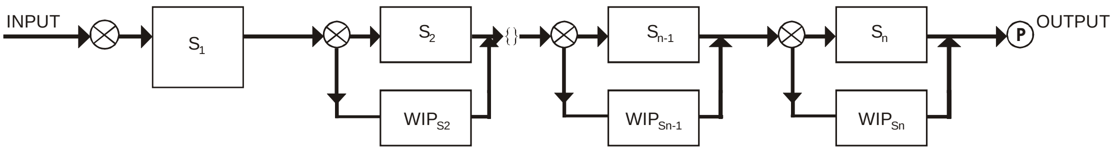

Figure 3 (b): Configuration under proposed approach of keeping WIP buffers (second type).

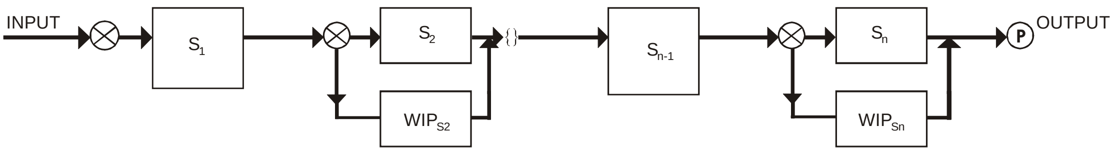

Figure 3 (c): Configuration under proposed approach of keeping WIP buffers (third type).

For better understanding, refer to Fig. 3 (a). Let sub-system S2 fails, then under this practice, the previous sub-system, say S1, will continue to process and that this generated output will be stored separately as WIP Buffer for that stage, say S1, of production till the next failed system, say S2, is repaired completely and brought in to operation back and flow to the next stage S2 will be from WIP Buffer being kept at stage S2. Once the failed system gets repaired, then the inflow of WIP i.e. semi-finished product from such sub-system (stage) in the manufacturing line to the next sub-system (next stage) is restored back. The WIP so generated will be just to balance or compensate loss of output from stage S2. This type of practice will ensure that required quantity of production *P* of required quality is achieved over time *T* i.e. 100 % reliability of production from the manufacturing line can be achieved.

3.1 Modus operandi to get WIP buffer

In this approach obviously question arises, that how to build buffers of WIP at various stages, as planned. Hence, for generation of buffers of WIP, four different alternatives have been suggested rather advocated. **First approach** which has been suggested [12] is to keep capacity of sub-systems or machines at each stage little more than the required capacity. Thus buffers will gradually be built up of required quantity and quality. However, under this practice, if adopted, two distinct disadvantages will be there which will heavily and adversely affect cost of production in two ways; one that initial cost and thereby recurring operating cost will be quite high and other that there can be heavy accumulation of buffers (if not required). **Second approach** which will be hybrid approach and as suggested here, and which will be cost optimal also, is to keep standby redundant sub-system of less capacity at 1st stage of production and can be operated to generate WIP of this type whenever need is anticipated. For rest of the stages of production, the WIP buffers can gradually be built up over times, whenever failure at any stage takes place. This can be explained/understood as; let the 3rd stage of production line fails then keep operating sub-systems at stage 1 and 2. By doing so, it will help to build up WIP buffers at stage 2. Similar practice is to be adopted at other stages of production line for building up WIP buffers during failure or downtime at other stage. Thus, on similar line WIP buffers can be built up at all the stages gradually. **Third approach** suggested here is to keep sub-system at 1st stage of production line of little higher capacity as suggested at approach one and also by [12] and at rest of the sub-systems, the practice as suggested at approach two to be adopted. In all these three suggested approaches, a distinct advantage will also be there, that there will be consistency of quality of WIP as per the process capability of each sub-system. There can also be a **fourth approach**, which suggests that one should buy WIP buffer of required quantity and quality from the market with proper tie up from their suppliers. This too can be cost optimal solution provided the supply is always time bound and of required quality too.

3.2 Benefits from proposed system

Under this new approach i.e. introduction of buffers of WIP at various stages, the configuration of the manufacturing line can be as depicted in Fig. 3 (a), (b) or (c). The overall effect of this approach is overwhelming, most promising, most cost effective, easily implementable, least disturbing, mostly automatic switch over (based on storing and handling arrangements made at each stage) and boosting reliability of overall continuous manufacturing system to 100 %. A mathematical derivation has been worked out to authenticate (this new approach) this work. Yet another big advantage of this approach will be that there will be consistency of quality of output from each stage.

4. REALIABILITY COMPARISON MADE UNDER DIFFERENT ARRANGEMENTS

Efforts are being made to show mathematically how reliability of giving rated production over time T compares under three different arrangements in a continuous manufacturing system. **First case** is, Serial Line Arrangements of machines. **Second case** is Parallel Standby Redundant Configurations of machines as proposed by [2] and others referred here in, in their papers. **Third case** is, instead of Parallel Standby Redundant Arrangements of machines, to have buffers of WIP at each stage of CMS much similar to Standby Redundant Parallel Arrangements.

4.1 Reliability under Serial Line Arrangement and under idealistic conditions (without failures over time *T* at any stage)

This is a conventional case of arranging machines in serial in any CMS as shown in Fig. 1. Let,

n - No. of sub-systems/stages in manufacturing line/system
RPT - Reliability of manufacturing line/system that will give P quantity of production over time T (rated capacity)
R_1S_1 - Reliability of sub-system at stage 1
R_nS_n - Reliability of sub-system at stage n

Then: $$RPT = R_1S_1 \times R_2S_2 \times R_3S_3 \times \ldots\ldots\ldots\ldots \times R_nS_n \quad (1)$$

which, in most of the cases will be quite less than 1. Let us presume, that $R_1S_1 = R_2S_2 = R_nS_n$ and each is equal to 0.8 than: 0.8 × 0.8 × … × 0.8 will always be quite less then 1. Thus, in serial line arrangement of machines, the reliability or the probability that such a system will give rated production over time T will always be less than 1 i.e. less than 100 %.

4.2 Reliability under Parallel Standby Redundancy Arrangement

Consider a segment of the manufacturing line, as depicted in Fig. 2 (a). Here only combination of one main and one standby machine has been considered. However, more than one machine in Standby Parallel Standby Redundancy has also been suggested by [4].

Say at stage i:
R_n - Reliability over time T of (in main line) sub-system S_i
$R_s B_i$ - Reliability over time T of standby redundant sub-system (SB_i)
Z_i - Reliability of composite or integrated sub-system
Q_i - Unreliability over time T of (main) sub-system
$Q_s B_i$ - Unreliability over time T of standby redundant sub-system (SB_i)

Then, the probability that both the Main sub-system and the redundant sub-system at stage i will fail at a time is the product of their unreliability. Hence,

$$X_i = Q_i \times Q_sB_i \quad (2)$$

X_i - Unreliability of the composite / integrated sub-system

The reliability and unreliability of the composite sub-system at stage i should be equal to 1. Thus,

$$Z_i + X_i = 1 \quad (3)$$

or

$$Z_i = 1 - X_i \quad (4)$$

on substituting the value of X_i:

$$Z_i = 1 - Q_i \times Q_sB_i \quad (5)$$

Let, the reliability at stage i of each sub-systems (main as well standby) over time T is 0.8 than unreliability of each will be (1-0.8) = 0.2 of each and therefore (considering one stage of production line):

$$Z_i = 1 - 0.2 \times 0.2 = 1 - 0.04 = 0.96 \quad (6)$$

Thus, it is evident that reliability under parallel standby redundant configuration gets enhanced from 0.8 to 0.96, thus definite improvement, but can not be 100 % in any case. Further, the initial investment on operation and maintenance cost will be exorbitant too, hence not an economical solution.

4.3 Reliability under new approach "Keeping Buffers of Work-In-Process at each stage" similar to Parallel Standby Redundant Sub-system

Here, the reliability analysis has been carried for the new suggested approach. The configuration has been depicted in Fig. 3 (a). As discussed earlier, instead of keeping standby sub-systems in parallel at each stage of CMS, just (better) keep buffers of WIP of required type, quantity and quality at each stages much alike to the standby redundant sub-system. As per this proposed approach, the whole CMS has been configured in this arrangement as depicted in Fig. 3.

Under this buffer of WIP approach, *the probability that flow of semi finished material (WIP) from stage i to next stage* i+1 *will not be there (by practice) is assumed to be zero*. This will be true, because in case of failure of machine at stage i, the flow of WIP will be made through buffer of WIP being kept at that stage. Thus, unreliability of flow from stage i to next stage in CMS under this arrangement (for that matter at any stage) will be zero (considering one stage of production line). Let,

Z_{wi} - Reliability of composite arrangement at i i.e. probability that continuity of supply from stage i to next stage i+1 will be maintained uninterrupted (by practice)

Q_i - Unreliability of sub-system at stage i

Q_{wi} - Unreliability of supply of WIP (semi finished product) to next stage i.e. non-supply from stage i to stage i+1 (which will be zero)

Q_{wi} = 0

X_{wi} - Unreliability of composite arrangement at i i.e. probability that continuity of supply of WIP to next stage i+1 will not be maintained

$$X_{wi} = Q_i \times Q_{wi} \tag{7}$$

$$Z_{wi} + X_{wi} = 1$$

Or on substituting the value of X_{wi}:

$$Z_{wi} = 1 - X_{wi} = 1 - Q_i \times Q_{wi} = 1 - Q_i \times 0 = 1 - 0 = 1 \tag{8}$$

$$Z_{wi} = 1 - 0.0$$

$$Z_{wi} = 1$$

5. A CASE STUDY CORRELATED SIMULATION

To test the authenticity and also the practical utility of this new approach, a case study has been made at one of the units of a multi unit organization. The unit is at Zinc Smelter – Plant located at Udaipur, Rajasthan (India). The organization is a multi unit and multi location organization, which is running round the clock, day in day out irrespective of holidays. It is a continuous manufacturing process plant, producing Zinc Metal. The plant is maintaining data bank. At the onset, it was told by the Management that this plant is running in heavy losses. However, the plant is kept running because of Government Support and to minimize Zinc Export, such that Country's requirement is met. Because of other profit making units, the whole organization was able to bear the losses of this unit. The detailed data were examined and required data summary was prepared and is presented below.

In Zinc producing plant in one of the smelting unit, the installed annual production capacity is 50,000 tonnes of finished Zinc of 99.97 % purity. The plant has been designed to work 300 days continuously. 65 days have been erring marked for shut down maintenance being the routine maintenance. The estimated cost of production is Rs. 1.20 Lacs per tones and prevailing selling price of Zinc is Rs. 1.50 Lacs per tonne. From the past record, what has been found is that there are in totality 100 breakdowns over the year during which entire production stops producing and hence there were loss of output. Every repair amounts to average 1.5 days of repair time. The actual production is as such average 25000 tonnes over the year.

Since plant is running in heavy losses, a feasible report has been made to find out which approach will be the most optimal so that profitability of the Company is maximized. If a standby parallel arrangement is thought of then Rs. 960 Crores is the initial cost estimate. And if WIP buffer approach is adopted, then inventory tieing up at each stage will cost Rs. 75 Lacs at each stage. The material handling cost at each stage is estimated to be Rs. 200 per tonne. Inventory carrying cost will be around 20 % of the inventory every year. The repair and maintenance cost on an average has been found to be Rs. 30 Crore/Annum. The whole manufacturing process can be considered to be split into four stages. From production point of view, as to which approach adopted can give 100 % rated capacity utilization over a year, the solution from field data have been worked under these three different arrangements (as discussed in previous paras). Let:

P - Planned production/year (50000 Tonnes)

p - Rate of production per day (50000/300 = 166.6 Tonnes/day)

n - No. of sub-systems (4 in this case)

PA - Actual production over time T (say a year)

PL - Loss of production over time T (say a year)

R_i - Reliability of each sub-system at each stage i taken for illustration purpose as 0.8

T - Designed or specified period of production (say a year = 300 days)

TA - Available time of system or sub-system over period T and everything presumed to be normal = $T \times \prod_{i=1}^{n} R_i$

t_{ij} - Mean repair time during j-th failure at any stage i = Average mean time to repair during any failure at any stage i (further averaging for simplicity) = 1.5 days in this case

q_{ij} - Quanity of buffer of WIP required at stage i during j-th failure, to feed to next stage i+1

5.1 Production achievement in case of “Serial Line Arrangement”

In this convention type of arrangement:

$$PA = p \times T \times \prod_{i=1}^{n} R_i \text{ , when } n = 4:$$

$$PA = 166.6 \times 300 \times (0.8 \times 0.8 \times 0.8 \times 0.8) = 166.6 \times 300 \times 0.4086 = 20472 \text{ Tonnes/year}$$

As against this the actual production over past few years was within the range 20000 Tonnes/year to 26000 Tonnes/year as against the planned capacity of 50000 Tonnes/year. Hence, the plant was running in losses for last few years. The above result is based on each sub-system’s reliability at each stage presumed to be 0.8. On this assumption, the results are more or less matching with actual.

5.2 Production Achievement “Parallel Standby Redundancy Arrangement”

From equation (3) above (Presuming that either main system or standby sub-system will be in operation throughout the time TA):

$Z_i = 1 – X_i$, presuming R_i of each sub-system at each stage is 0.8.

$X_i = Q_i \times Q_s B_i$

$Z_i = 1 – (0.2 \times 0.2 \times 0.2 \times 0.2) = 1 – 0.0016 = 0.9984$

$TA = T \times Z_i$

$PA = p \times TA = p \times T \times Z_i = 166.6 \times 300 \times 0.0084 = 49900$ Tonnes/year

If parallel standby system with reliability presumption of 0.8 is applied, the production or output can touch a figure of 49900 Tonnes/year but not 100 % of rated capacity of 50000 Tonnes/year. Moreover, this also demands installation of almost a parallel standby plant. Hence, cost of installation and recurring will at least be **just double** of estimated cost of production under conventional arrangement, hence not advised at all.

5.3 Production achievement & Modus operandi of "WIP Buffer Arrangement"

In the study of the plant, averaging of the failures has been done and it has been estimated that whenever a major breakdown of sub-system takes place, then it takes almost 1.5 day to restore the back production. However, in real life situation the repair time will keep on varying and hence suppose at some stage, it takes 2 days to restore production from that stage, then at rest of the previous stages production will continue and thus WIP will be generated at stage next to failed stage for 2 days. Thus, quantity of WIP buffers at various stages will keep on varying and can be well met out by this approach. Once requirement of WIP buffer is met fully, then that reliability of production will always be 1.0 i.e. 100 %. In this arrangement, as stated above the reliability of continuous production from stage *i* will be $R_i = 1$ and therefore:

$$PA = p \times T \times \prod_{i=1}^{n} R_i = p \times T \times R_1 \times R_2 \times R_3 \times R_4 = p \times T \times 1 \times 1 \times 1 \times 1 = p \times T$$

$PA = 166.66 \times 300 \approx 50000$ Tonnes/year

Thus PA equals P i.e. planned capacity.

The quantity of minimum WIP buffers of required type to be kept at each stage will be:

$q = p \times t = 166.66 \times 1.5 = 250$ Tonnes

Say at 4 stages of production 250 Tonnes minimum of WIP buffer of required type will be needed to be kept so that during failure at any stage, the WIP is supplied from this buffer. In case of process industry, separate storage bins and material flow connection are to be made through which materials (WIP) flow can be diverted whenever need arise. In part manufacturing industry also a material (WIP) flow line (Material Handling System) will be required to divert flow from WIP buffers from one stage to next stage and so on till the end product.

6. CONCLUSION

The conventional CMS (i.e. Serial Line Arrangement), the Parallel Standby Redundant System and the proposed "Buffers of Work-In-Processes System" in CMS have been discussed and analyzed. The proposed system has been described and illustrated in Fig. 3. The reliability analysis in all the three cases has been carried out. It has been mathematically derived and proved that in the case of proposed system, if at each stage of CMS buffer of WIP of required quantity, quality and type is kept, then the reliability of CMS to give rated production over time *T* will be 100 % i.e.1.

The proposed approach is generally applicable in mass production system but can easily be used in batch production system and process industries as well. There are other numerous advantages of this approach such as on quality front, production front, cost and profitability front which are under process of modelling and simulation. Industries should adopt such approach so as to derive maximum benefit.

7. FURTHER SCOPE

In case this WIP buffer approach is adopted, then what will be the additional cost built over the initial estimated cost of production, what will be the enhancement on productivity and profitability front are the areas to be explored further. At the onset it is visualized that these parameters will be most optimal compared to any previous approaches, as contributed by the researcher. Another area to be explored is the statistical generation of failure rates at various stages and accordingly requirement of buffer stocks etc. at each stage. This can of course be developed on random number generation and different types of distribution curve say Poisson distribution or Weibul distribution in case of mechanical component depending upto the type of system and the quality of maintenance etc. Based on some realistic concept; the probability of mission WIP can further be explored and can be proved to be zero.

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