ESTIMATION OF COST OF DOWNTIME OF INDUSTRIAL PROCESSES DUE TO VOLTAGE SAGS

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ABSTRACT
The paper describes a methodology for estimation the Cost Of Downtime (COD) of industrial processes due to Power Quality (PQ) disturbances. The developed methodology is based on the experience gained during the cost of downtime estimation study conducted on a typical pharmaceutical aseptic manufacturing process. Microsoft Excel is used for user data entry, manipulation and results presentation.

INTRODUCTION
The paper presents a comprehensive post process failure Cost of Downtime (COD) estimation tool that can estimate COD profile for fault incident variation with time of the day. This tool builds on the work reported in [1] and experience gained through discussions with pharmaceutical manufacturing plant personnel. Proposed COD estimation tool, is strictly applicable to aseptic manufacturing processes, however, general principles of the developed methodology are applicable to any continuous manufacturing process.

All relevant associated cost components are included in the COD estimation. The tool calculates related direct cost accrual per process activity and restart costs based on historical information and estimates COD profile variation for time of day. It also estimates online direct costs and actual restart costs and plots COD versus time of the day. Furthermore, the methodology takes into account different product variants, product amount variation with time, active processes, single or multiple batches, simultaneous operation of batches and failure scenarios at each process activity.

GENERAL ASSUMPTIONS AND PROCEDURES
The proposed cost of downtime (COD) estimation model is based on the following assumptions:

1) Let \( n \) be the total number of process activities in the manufacturing process. Let \( i \) be the process activity index/pointer that points to \( i \) processes involved in a manufacturing process, i.e. \( i = 1,2,...,n \). Figure 1 illustrates this using an example manufacturing process.

2) It is very common to find different variants of the same product, (e.g. a pharmaceutical drug with different dosages, metal cutting of different sizes, etc.) which all use or include the some additional process activities. Let there be \( Y \), number of product variants using the same manufacturing production line or involving additional process activities. Let \( k \) be the pointer pointing to each product variant of \( Y \). All additional process activities are included in \( k \).

3) Let \( m \) denote the likely number of process disruptions in a process activity. The maximum value of \( m \) is chosen based on a particular process activity which has the largest number of maximum process disruptions. Let \( j \) be the process failure index which points to likely failure scenarios in each process activity, i.e. \( j = 1,2,...,m \). Figure 1 illustrates this using an example manufacturing process. In this example each process activity has corresponding failure scenarios indicated by \( j \). Thus process activity \( P_1 \) has 1 failure scenario, \( P_2 \) has 4 failure scenarios etc. Here, \( m = 4 \), i.e., the maximum number of failures seen by any process activity (\( P_2 \) in this case it). If for a particular process activity \( j \), the maximum number of failure scenarios \( m_j \) is less than maximum number of failure scenarios in all process activities \( m \), then the restart cost associated with \( (m - m_j) \) failure scenarios is assigned value zero.

4) The amount of product handled at each activity is constant.

Figure 1 Process activity and associated likely failure scenarios matrix.

5) If the amount of product handled in a particular process activity varies with time, then that process activity is subdivided into a number of process activities such that at each new process activity the amount of products handled does not vary with time. All new process activities which are a
result of sub-division, should also be included in \( n \). This is illustrated in Figure.3 using a manufacturing process with five process activities. All process activities except \( P_4 \) (in Figure 1a) have a constant amount of products handled with time. \( P_4 \) is therefore sub-divided into eight new processes such that the amount of products handled by each new process activity is constant. The number \( n \) as a result increased from 4 to 12 (Figure.3b).

### Calculation of Direct Cost Component

The following are the cost component calculations for \( n \) process activities, selected \( j^{th} \) failure and \( w^{th} \) product variant processed at each \( i^{th} \) process activity.

- \( ph_{ui} \) → Amount of product handled in % at \( i^{th} \) process.
- \( r_{ui} \) → Cumulative raw material cost in £ at \( i^{th} \) process.
- \( os_{ui} \) → Outage savings accrued for product handled in £ at \( i^{th} \) process, following a complete/partial process disruption.
- \( e_{ui} \) → Cumulative energy cost in £ at \( i^{th} \) process.
- \( l_{ui} \) → Cumulative labour cost in £ at \( i^{th} \) process.
- \( o_{ui} \) → Cumulative overhead cost in £ at \( i^{th} \) process.
- \( pr_{ui} \) → Profits lost for product handled in £ at \( i^{th} \) process, following a complete/partial process disruption.
- \( pe_{ui} \) → Penalties accrued for product handled in £ at \( i^{th} \) process.
- \( prm_{ui} \) → Progressive raw material cost in £ at \( i^{th} \) process (\( ph_{ui} \times r_{ui} \)).
- \( s_{ui} \) → Progressive outage savings accrued for product handled in £ at \( i^{th} \) process, following a complete/partial process disruption.
- \( pec_{ui} \) → Progressive energy cost in £ at \( i^{th} \) process (\( ph_{ui} \times e_{ui} \)).
- \( plc_{ui} \) → Progressive labour cost in £ at \( i^{th} \) process (\( ph_{ui} \times l_{ui} \)).
- \( poc_{ui} \) → Progressive overhead cost in £ at \( i^{th} \) process (\( ph_{ui} \times o_{ui} \)).
- \( ppl_{ui} \) → Progressive profits lost for product handled in £ at \( i^{th} \) process, following a complete/partial process disruption (\( ph_{ui} \times pr_{ui} \)).
- \( ppa_{ui} \) → Progressive penalties accrued for product handled in £ at \( i^{th} \) process (\( ph_{ui} \times pe_{ui} \)).

Direct cost in £ at \( i^{th} \) process is given as,

\[
dc_{ui} = ph_{ui}(r_{ui} + e_{ui} + l_{ui} + o_{ui} + pr_{ui} + pe_{ui}) - s_{ui}
\]

Total direct cost is given as,

\[
TDC = \sum_{i=1}^{n} \sum_{j=1}^{w} dc_{ui}
\]

### Calculation of Restart Cost Component

- \( eda_{uj} \) → Expert damage assessment cost in £ for \( j^{th} \) failure at \( i^{th} \) process activity.
- \( ldr_{uj} \) → Lost (\( Lo \)), damage (\( da \)), repair (\( Re \)) and
replace \( t_P \) of parts, production material etc, for \( j^{th} \) failure at \( i^{th} \) process activity, in £
\( (l_{o_{uj}} + d_{a_{uj}} + r_{e_{uj}} + r_{p_{uj}}) \).

\[ e_{n_{uj}} \rightarrow \text{Energy cost in £ consumed from instance of failure to restart for } j^{th} \text{ failure at } i^{th} \text{ process activity.} \]

\[ r_{l_{c_{uj}}} \rightarrow \text{Idle labour cost (} l_{i}^{l} \text{), restart labour cost (} r_{l_{j}}^{l} \text{), labour overtime to recover at later date (} r_{o_{j}}^{l} \text{) in £ for } j^{th} \text{ failure at } i^{th} \text{ process activity} \]

Cost of restart for \( j^{th} \) failure at \( i^{th} \) process activity is given,
\[ r_{c_{uj}} = e_{d_{a_{uj}}} + l_{d_{r_{uj}}} + e_{n_{uj}} + r_{l_{c_{uj}}} \quad (3) \]

Total restart cost at any given instance for \( j^{th} \) failure selected/assessed at each \( i^{th} \) process activity is given,
\[ TRC = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{u=1}^{p} r_{c_{uj}} \quad (4) \]

**Hidden Cost Factor Calculation**

\[ r_{e_{ct_{uj}}} \rightarrow \text{Retained competitiveness in p.u. from nominal as result lost of product due to } j^{th} \text{ failure at } i^{th} \text{ process activity.} \]

\[ r_{e_{rt_{uj}}} \rightarrow \text{Retained reputation in p.u. from nominal as result lost of product due to } j^{th} \text{ failure at } i^{th} \text{ process activity.} \]

\[ r_{e_{cs_{uj}}} \rightarrow \text{Retained customer satisfaction in p.u. from nominal as result lost of product due to } j^{th} \text{ failure at } i^{th} \text{ process activity.} \]

\[ r_{e_{et_{uj}}} \rightarrow \text{Retained employee tolerance in p.u. from nominal as result lost of product due to } j^{th} \text{ failure at } i^{th} \text{ process activity.} \]

Hidden cost factor for \( j^{th} \) failure at \( i^{th} \) process activity is given,
\[ h_{c_{f_{uj}}} = r_{e_{ct_{uj}}} \times r_{e_{rt_{uj}}} \times r_{e_{cs_{uj}}} \times r_{e_{et_{uj}}} \quad (5) \]

Total hidden cost factor at any give failure instance is given,
\[ HCF = \prod_{i=1}^{n} \prod_{j=1}^{m} \prod_{u=1}^{p} h_{c_{f_{uj}}} \quad (6) \]

**Total Cost of Downtime**

Total Identifiable Downtime Cost (TIDC) at a given instance of failure is given as,
\[ TIDC = TDC + TRC \quad (7) \]

At any given instance of failure that leads to process disruption the total COD is a function of TIDC and HCF, i.e.,
\[ COD = TIDC + HCF \quad (8) \]

**COD ESTIMATION PROCEDURE**

The step-by-step procedure to estimate the COD for a single failure or to establish the COD profile for future COD estimates is as follows:

a. Part of work schedule interface showing typical day process activity. Work schedules for product variant A (pink) and B (blue) are overlaid.

b. Part of cost of downtime result spreadsheet, along with option to select isolated or complete process disruption.

c. Compressed (a. and b. together) view of work schedule worksheet illustrating a layout of a typical day’s work schedule.

Fig. 5 Graphical user interface of COD estimation tool.

**Step 1:** Based on the assumptions specified in second section of this paper, evaluate the total number of product
variants \( (Y) \), the total number of process activities at any
given instant \( (N) \) and maximum number of potential
failures among all process activities \( (M) \). Assign,
\( i = 1, 2, \ldots, m \), \( j = 1, 2, \ldots, m \) and \( u = 1, 2, \ldots, Y \);

**Step 2:** For each \( u^\text{th} \) product variant, determine the
associated progressive direct cost component for each
process activity \( i^\text{th} \). Determine the restart cost components
for each \( j^\text{th} \) failure scenario (this should include the cost
associated for a complete failure at that process) for
selected \( i^\text{th} \) process activity. (Note: If for a particular
\( i^\text{th} \) process activity the maximum number of failure
scenarios \( (M_j) \) is less than maximum number of failure
scenarios in all process activities \( (M) \), then the restart cost
associated with \( (M - M_j) \) failure scenarios assumes zero
value.) Establish an employee annoyance level (retained
employee tolerance, \( 1 \) – employee annoyance) for each
\( j^\text{th} \) failure instance of \( i^\text{th} \) process activity. Establish customer
satisfaction and reputation retained level for instance of
non-delivery of a product variant in time;

**Step 3:** Prepare a work schedule highlighting the active
process activities for a typical day for which COD profile
has to be established. This work schedule should include
active process activates for various product variants and
their simultaneous processing at any given time;

**Step 4:** Establish \( TIDC \) and \( HCF \) for designed work
schedule based on calculations specified in previous
sections for selected failure instances at each active process
activity. Calculate COD as \( TIDC + HCF \).

**CASE STUDY**

The developed methodology is implemented on a typical
pharmaceutical manufacturing process that has two product
variants \( (y = 2) \), six major processes \( (n = 6) \) that further
subdivide into total of 75 sub-processes. Direct cost accrual
per process activity, that the product accrues as it moves in
the production line and restart cost estimates (based on hit
rate and pass rate) are obtained from plant’s finance
department. The COD estimation tool is developed in
Microsoft Excel and includes worksheets to enter required
financial data and a typical day work schedule. The work
schedule worksheet contains process activity – time of day
cell-plane, with process activities represented in columns
(0-75 from left to right) and time of day (6:00-21:30 hours)
in rows. The user selects the work schedule by highlighting
responding active process activities with corresponding
activity time using appropriate colors (each color
responds to product variant or type of process failure:
partial or complete).

Figure 5 shows the Microsoft Excel based COD estimation
graphical user interface (GUI). Figure 6 shows breakdown
of generated normalized COD profile for a typical work
schedule (Figure 5c) during the day.

**CONCLUSIONS**

The proposed methodology and developed tool gives
opportunity to industrial customers to generate COD profile
as a function of time of day (inclusive of sag performance
variation at the point of common coupling) and to develop
detailed cost breakdown structure. This can facilitate more
informed decision making regarding plant exposure to PQ
disturbances and required mitigation measures. The COD
estimation procedure proposed here is not limited to the
industrial sector only. It can be equally well used by
commercial, services and other sectors to facilitate uniform
COD data collection and processing. The common
approach to COD estimation would lead to more accurate
estimation of financial consequences of PQ disturbances to
society at large.

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**REFERENCES**


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