

Counting Processes and Asymptotic Theory

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Failure Time Models,
5th chapter of *The Statistical Analysis of Failure Time Data*
Kalbfleisch and Prentice, 2002

Outline

- » Counting processes and intensity functions
- » Martingales
 - » Continuous-time counting processes
 - » Discrete-time counting processes
- » Martingale central limit theorem: Rebolledo's Theorem



A counting process $N = \{N(t), t \geq 0\}$

is a stochastic process with $N(0) = 0$ and whose value at time t counts the number of events that have occurred in the interval $(0, t]$.

- » The sample paths of N are nondecreasing step functions that jump whenever an event (or events) occur.
- » In continuous time,

no two counting processes can jump at the same time.

- » In discrete time, they can.

Number of events that occur in the interval $[t, t + dt)$?

$$dN(t) = N(t^- + dt) - N(t^-).$$

Number of events that occur at time t ? $\Delta N(t) = N(t) - N(t^-)$.

And what about more general counting processes where individuals may experience more than one event? Chapters 8, 9, and 10.



Filtration: history of events

observed counting process: $N_i = \{N_i(t), t \geq 0\}$

underlying counting process: $\tilde{N}_i = \{\tilde{N}_i(t), 0 \leq t\}$, $\tilde{N}_i(t) = \mathbf{1}(T_i \leq t)$

at-risk process: $\{Y_i(t), t \geq 0\}$, $Y_i(t) = \mathbf{1}(T_i \geq t, C_i \geq t)$

key concept: **filtration**

$$\mathcal{F}_t = \sigma\{N_i(u), Y_i(u^+), X_i(u^+), i = 1, \dots, n; 0 \leq u \leq t\}, \quad t > 0,$$

where

$$Y_i(u^+) = \lim_{s \rightarrow u^+} Y_i(s);$$

stochastic time-dependent covariate: $X_i(t) = \{x_i(u) : 0 \leq u \leq t\}$.

The notation $\sigma[\cdot]$ specifies the **sigma algebra of events** generated by the variables given in the brackets.



Intensity functions

The intensities or rates for the processes N_i are defined with reference to the filtration \mathcal{F}_t . If the censoring process is independent, the **intensity model** for the counting process N_i is

$$\mathbb{P}[dN_i(t) = 1 | \mathcal{F}_{t-}] = Y_i(t) d\Lambda_i(t), \quad i = 1, \dots, n, \quad t > 0.$$

The hazard model can be written $d\Lambda_i(t) = \mathbb{P}[d\tilde{N}_i(t) = 1 | X_i(t), \tilde{N}_i(t^-) = 0]$.

Λ_i is called the **cumulative intensity process** of the counting process \tilde{N}_i .

- » In the continuous case, $\mathbb{P}[dN_i(t) = 1 | \mathcal{F}_{t-}] = Y_i(t) \lambda_i(t) dt$
- » In the discrete case, $\mathbb{P}[dN_i(a_l) = 1 | \mathcal{F}_{a_l-}] = Y_i(a_l) \lambda_{il}, \quad l = 1, 2, \dots$

$\lambda_i(t)$ and λ_{il} are the corresponding **intensity processes**.



Martingales: Intro

$$\begin{aligned}M_i(t) &= N_i(t) - \int_0^t Y_i(u) \lambda_i(u) du, \quad t \geq 0. \\&= \int_0^t dM_i(u), \\dM_i(t) &= dN_i(t) - Y_i(t) \lambda_i(t) dt.\end{aligned}$$

If

$$\gg \mathbb{E}[dM_i(t) | \mathcal{F}_{t-}] = 0, \quad \forall t; \quad \equiv \quad \mathbb{E}[M_i(t) | \mathcal{F}_s] = M_i(s), \quad \forall s \leq t.$$

Then, $M_i(t)$ is a **martingale**.

Consequences:

- $\gg \mathbb{E}[M_i(t)] = 0, \quad \forall t;$
- \gg the process $M_i(t)$ has uncorrelated increments, i.e.,
 $\mathbb{E}[(M_i(t) - M_i(s)) \times M_i(s)] = 0, \quad \forall 0 < s < t.$



Decomposing $N_i(t)$ into two processes

$$N_i(t) = \underbrace{\int_0^t Y_i(u) \lambda_i(u) du}_{\text{compensator of the counting process } N_i \text{ wrt the filtration } \mathcal{F}_t} + \underbrace{M_i(t)}_{\text{counting process martingale corresponding to } N_i(t)}$$

$$dN_i(t) = Y_i(t) \lambda_i(t) dt + dM_i(t).$$

In the discrete case, the discrete-time martingale is

$$\begin{aligned} N_i(t) &= \int Y_i(u) d\Lambda_i(u) + M_i(t) \\ &= \sum_{a_l \leq t} Y_i(a_l) \lambda_{il} + M_i(t), \\ dN_i(a_l) &= Y_i(a_l) \lambda_{il} + dM_i(a_l). \end{aligned}$$



More about martingales

In essence, a **martingale** is a process that has no drift and whose increments are uncorrelated.

- » We say that $M(t)$ is a mean zero **martingale** if $\mathbb{E}[M(0)] = 0$, and hence $\mathbb{E}[M(t)] = 0, \forall t$.
 - » The martingale $M(t)$ is said to be **square integrable** (or have finite variance) if $\mathbb{E}[M^2(t)] = \mathbb{V}[M(t)] < \infty, \forall t \leq \tau$.
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It is useful to define two technical terms applied to a stochastic process $U = \{U(t), t \geq 0\}$.

Adapted

U is said to be **adapted** to the filtration \mathcal{F}_t if $U(t)$ is \mathcal{F}_t measurable for **each** $t \in [0, \tau]$, i.e., the value of $U(t)$ is fixed once \mathcal{F}_t is given.

Predictable

U is said to be **predictable** wrt the filtration \mathcal{F}_t if $U(t)$ is \mathcal{F}_{t-} measurable for **all** $t \in [0, \tau]$, i.e., the value of $U(t)$ is fixed once \mathcal{F}_{t-} is given.

More about martingales

The process $\{\bar{M}(t), 0 \leq t \leq \tau\}$ is a **submartingale** wrt \mathcal{F}_t if it is **adapted** and satisfies

$$\mathbb{E}[\bar{M}(t)|\mathcal{F}_s] \geq \bar{M}(s) \quad \forall s \leq t \leq \tau.$$

» A counting process $N(t)$ is a **submartingale**.

Predictable variation process

The **predictable variation process** of a square-integrable martingale M is

$$\langle M \rangle(t) = \int_0^t \mathbb{V}[dM(u)|\mathcal{F}_{u-}].$$

Equivalently, $d\langle M \rangle(t) = \mathbb{V}[dM(u)|\mathcal{F}_{u-}]$.

In statistical terms, the primary role of the **predictable variation process** is that for given t , $\langle M \rangle(t)$ provides a systematic approach to estimating the variance of $M(t)$.



Variance of $M(t)$

$$\mathbb{V}[M(t)] = \mathbb{E}[M^2(t)] = \mathbb{E}[\langle M \rangle(t)]$$

and $\langle M \rangle(t)$ is an **unbiased** estimator of $\mathbb{V}[M(t)]$.

Usually, $\langle M \rangle(t)$ involves the parameters of the model.

There is an alternative estimator of $\mathbb{V}[M(t)]$ that in some problems is a function of observed quantities only. This is the **quadratic variation** or **optional variation process** $[M](t)$.

$$[M](t) = \sum_{s \leq t} (\Delta M(s))^2.$$

$[M](t)$ also provides an **unbiased** estimator of $\mathbb{V}[M(t)]$.



Continuous-time counting processes

For each i , the process

$$M_i(t) = N_i(t) - \int_0^t Y_i(u) \lambda_i(u) du$$

is a mean zero **martingale** wrt the filtration \mathcal{F}_t . The corresponding **predictable variation process** is

$$\langle M \rangle(t) = \int_0^t Y_i(u) \lambda_i(u) du$$

since $d\langle M \rangle(u) = \mathbb{V}[dM(u)|\mathcal{F}_{u-}] = \mathbb{E}[dN_i(u)|\mathcal{F}_{u-}] = Y_i(u) \lambda_i(u) du$, $0 \leq u \leq \tau$. The **optional variation process** is

$$[M_i](t) = N_i(t).$$

Both $\langle M_i \rangle(t)$ and $[M_i](t)$ provide unbiased estimates of $\mathbb{V}[M_i(t)]$, but only the latter is a function of the data only.



Discrete-time continuous processes

In discrete time we have

$$\mathbb{P}[dN_i(t) = 1 | \mathcal{F}_{t-}] = \mathbb{E}[dN_i(t) | \mathcal{F}_{t-}] = Y_i(t) d\Lambda_i(t),$$

where $\Lambda_i(t) = \sum_{a_l \leq t} \lambda_{il}$ and λ_{il} are the discrete hazard probabilities.

The corresponding **martingale** is

$$M_i(t) = N_i(t) - \int_0^t Y_i(u) d\Lambda_i(u)$$

and the **predictable variation process** is

$$\langle M_i \rangle(t) = \sum_{a_l \leq t} Y_i(a_l)(1 - \lambda_{il})\lambda_{il}.$$

The increment $d\langle M_i \rangle(t)$ at a_l corresponds to
 $\mathbb{V}[dN_i(a_l) | \mathcal{F}_{t-}] = Y_i(a_l)(1 - \lambda_{il})\lambda_{il}.$



Martingale central limit theorem: Rebolledo (1980)

The central limit theorem due to Rebolledo (1980) is the main result useful for asymptotics in the applications of the book. This theorem drew together earlier work on central limit theorems for discrete martingales and gave a general version applicable to martingales arising from counting processes in discrete time, continuous time, or a mixture of the two.

What do we need? A vector of k martingales, $U^{(n)}$, where

$$U_j^{(n)}(t) = \sum_{i=1}^{r_n} \int_0^t G_{ji}^{(n)}(s) dM_i^{(n)}(s), \quad j = 1, \dots, k.$$

$G_{ji}^{(n)}(t)$ are predictable processes.

For given $\epsilon > 0$, we define a vector of related processes,

$$U_{\epsilon j}^{(n)}(t) = \sum_{i=1}^{r_n} \int_0^t G_{ji}^{(n)}(u) \mathbf{1}(|G_{ji}^{(n)}(u)| > \epsilon) dM_i^{(n)}(u),$$

$j = 1, \dots, k$, $t \in [0, \tau]$, which registers all jumps of size ϵ or more in the original component processes $U_j^{(n)}$.



Rebolledo's Theorem

Idea: Consider conditions under which the distribution of $U^{(n)}$ approaches a normal limit as $n \rightarrow \infty$.

[Rebolledo's] Let t be a fixed time in $[0, \tau]$ and consider the conditions:

- (a) $\langle U^{(n)} \rangle(t) \xrightarrow{\mathcal{P}} V(t)$ as $n \rightarrow \infty$.
- (b) $[U^{(n)}](t) \xrightarrow{\mathcal{P}} V(t)$ as $n \rightarrow \infty$
- (c) $\langle U_{\epsilon_j}^{(n)} \rangle(t) \xrightarrow{\mathcal{P}} 0$ as $n \rightarrow \infty$, $\forall j = 1, \dots, k$ and $\epsilon > 0$.

Then either (a) or (b) together with (c) imply that $U^{(n)}(t) \xrightarrow{\mathcal{D}} N(0, V(t))$.



